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D. F. Cottrell, et al

Martin Marietta Corporation
Orlando, Florida

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Final Report

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

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A 22 month program has been conducted to determine the effects of dormant operating and storage conditions on electronic equipment and parts. An extensive data search has been made covering major aerospace industries, research institutes, and government agencies. The program also employs data from tests on Martin Marietta parts and equipment with known storage histories.

Over 760 billion part-hours of dormant operating and storage information on various part classes have been collected from all sources. Of these data, approximately 76 billion part-hours are on military standard parts, 52 billion on selected military standard parts, 630 billion on high reliability parts, and 3 billion on microcircuits.

These data have been processed and are presented in the form of storage or dormant operating failure rates by part type and subtypes for the various part classes. Failure rate charts have been constructed and partially validated for military standard and for high reliability part classes. Environmental effects of dormant operation and storage on the various part classes are discussed together with some factors relating them to each other whether in the dormant operating or storage mode.

Test data from Martin Marietta storage programs have been statistically analyzed to determine performance drift trends with nonoperating time. Part failures that occurred during storage were dissected in the laboratory and failure mechanisms isolated.

Modeling techniques have been developed to show the methods by which realistic weapon system operational concept decisions are made to obtain maximum reliability. The use and validation of operational readiness models in making predictions are shown.


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| Dormant Operating Reliability | | | | | | |
| Degradation | | | | | | |
| Operational Readiness | | | | | | |
| Storage Reliability | | | | | | |



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Test data from Martin Marietta storage programs have been statistically analyzed to determine performance drift trends with nonoperating time. Part failures that occurred during storage were dissected in the laboratory and failure mechanisms isolated. Case histories of these analyses and a list of mechanisms found after nonoperating time periods are included in the appendices of this report. The failure mechanism list includes the experience of both Martin Marietta and other contractors as noted in the literature.

Design notes, prepared for various high-usage parts, detail the preferred application, procurement, vendor manufacturing, and user assembly practices. These practices are shown to result in maximum reliability during nonoperating time periods.

Modeling techniques have been developed to show the methods by which realistic weapon system operational concept decisions are made to obtain maximum reliability.

The use and validation of operational readiness models in making predictions are shown. Techniques by which better weapon system design decisions can be made to maintain the required operational readiness at any time in the electronic system life cycle are also presented. Finally, comparisons between nonoperating survival predictions and actual field observations have been made and included herein.

EVALUATION

1. The objective of this study was the development of quantitative information describing the reliability of electronic equipment and parts when subjected to storage and dormant stresses.

2. A large body of data was collected that enabled the development of failure rate values for high population parts of several quality levels. The information was also sufficient enough to show the effects of equipment packaging and storage locations. The results of this study will help to satisfy the requirements of Ogden Air Materiel Area and the Ballistics Systems Division who had stated their need for such data in planning and supporting future missile systems.

3. While the study was fairly comprehensive, there are gaps in the data on certain types of parts. Also, data on drift failures were scarce. This situation can be improved by the Reliability Analysis Central.

Lester J. Gubbins

LESTER J. GUBBINS
Reliability Engineering Section
Reliability Branch

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# SECTION 1

# INTRODUCTION

Unusually high maintenance requirements experienced by electronic equipment in use with the military services in the early 1960's has led to a concentrated study of dormant operating and storage conditions. The problem assumed increased importance because operational readiness could be significantly affected by failures during these nonoperating modes. Other questions arose such as: How often should equipment in storage or dormant operation be tested? What kind of failures should be expected? What action can be taken to reduce nonoperating failures?

During this period, Martin Marietta Corporation initiated an industry-wide survey which revealed that very little storage failure rate information was available. A search for storage degradation data on component parts (Reference 1), which was conducted in 1964, concluded that verification data appear to be virtually nonexistent.

The storage mode has been defined as the state wherein a device is not connected to a system but is packaged for preservation and experiences somewhat benign environments. Dormant operation is the state wherein a device is connected to a system in the normal operational configuration and experiences below normal or periodic electrical and environmental stresses for prolonged periods up to 5 years or more before being used in a mission.

In order to gain a better understanding of nonoperating failure rates and mechanisms, Rome Air Development Center awarded Contract AF30 (602)-3772 to Martin Marietta Corporation in May 1965.

## SECTION 2

## SUMMARY

This contract has resulted in the collection and analysis of nonoperating data in excess of 760 billion part-hours (one part times one nonoperating hour = one part-hour) of experience. The maximum storage age of equipment on which this analysis is based is 7 years. None of this information has previously been available to the aerospace industry, therefore, many of the deficiencies which have been found in reliability modeling techniques can now be alleviated.

Present day prediction methods for electronic systems consider electrical stress, temperature stress, and use environment. This study program has shown, however, that such factors as parts screening techniques, tolerance margins in application of parts, and the design of test and checkout equipment play an even more important role in determining part failure rates. Accurate quantification of these factors results in major improvements in both prediction techniques and reliability control during design, manufacturing, and use of a weapon system.

The nonoperating failure rate has been shown to be applicable to all electronic systems observed, and this fact provides a significant advance in reliability analysis. Using these failure rates, it is now possible to make more exact system predictions, tradeoff studies, and other reliability decisions.

Mathematical models using nonoperating failure rates can now be used to to predict operational readiness early in the contract definition phase by merely knowing the total number and type of electronic parts in the system being analyzed. This is a noticeable improvement from the past when systems not inherently capable of surviving nonoperating periods were not detected until well into the field use phase, some 5 to 7 years after initial design.

This report will also facilitate the establishment of criteria that will enable new equipment to withstand long term storage or dormant operation. In addition, it will make possible the development of techniques for obtaining maximum performance from existing equipments that have been designed without these criteria.

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# SECTION 3

# MARTIN MARIETTA TEST PROGRAM

## A. DESCRIPTION

The data presented in this section are from Martin Marietta tests on eight different hardware groups shown in Table I. Data for nonoperating failure rates have been collected on electronic parts and equipments used in several Martin Marietta programs. In order to analyze the effects of storage, a comparison of parameter measurements before and after storage was required. Not all parameters had been measured prior to placing the hardware in storage. Therefore, the data presented represent only the measurements that could be made within the limitations imposed by the earlier test programs.

To determine the effects of turn-on transients and repeatability of test equipment, and to segregate transient failures from storage induced failures, back to back testing techniques were used. This method entailed testing the items twice in close succession, reducing the time between tests to as near zero as possible.

Many times failure analysis will reveal mechanisms which are definitely time dependent. However, another study (Reference 69) was performed to assure that failures ascribed to storage were not really due to the turn-on transients of the failure detection tests. This assurance was provided by life test data on Pershing ground equipment which was monitored for failure during 162 turn-on cycles. After seven months storage, the equipment was turned on once again. The statistical evidence clearly showed that the number of failures produced by the 163rd turn-on cycle could not be due to turn-on transients alone and that degradation had also occurred during the seven months of storage.

### 1. Printed Circuit Boards (Group A)

With a known history of qualification tests, life tests, and/or age and deterioration tests, 909 printed circuit boards were taken from a 2 to 4 year storage period in a warehouse which was under a semitropical

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environment, and tested for the effects of storage. There was no visible evidence of fungus. Testing was conducted in a controlled environment using a printed circuit test console.

TABLE I

Hardware Groups in Martin Marietta Test Program

| Type | Sample Size | Storage Duration | Average Temp (°F) | Average R. H. (%) |
|---|---|---|---|---|
| Printed circuit boards (Group A) | 909 | 2 to 4 years | 72 | 90 |
| Printed circuit boards (Group B) | 215 | Various | 72 | 90 |
| Chassis assemblies | 114 | 1 to 2 years | 72 | 90 |
| Parts | 1,356 | 1 year | 72 | 60 |
| Ultrasonically cleaned printed circuit boards | 75 | > 3 years | 72 | 60 |
| Micromodules | 1,506 | 1 year | 72 | 90 |
| Test console parts | 584 | > 2 years | 72 | 90 |
| Microcircuits | 165 | 2 to 3 years | 72 | 60 |

Testing was conducted in two cycles. Cycle I consisted of complete testing of the boards using back-to-back testing techniques, failure determination, repair, and subsequent return to storage. Cycle II consisted of a duplication of this sequence after approximately 6 months of storage following Cycle I.

2. Printed Circuit Boards (Group B)

Group B consisted of 215 printed circuit boards that were made available for storage tests but whose previous history was not completely documented. Therefore, the boards were tested for circuit parameters and the individual parts comprising the circuits were then tested for tolerance drift. Data from these tests were used for part drift analysis (Reference 58, section 4B).

3. Chassis Assemblies

A total of 114 chassis assemblies from prior test programs involving qualification, life, and/or test-to-failure tests were also used for the storage tests. The chassis had been stored on warehouse shelves in a semitropical environment for 1 to 2 years. Testing was conducted using specially designed test sets which supply the necessary power sources and equipment indicators to verify proper operation of its chassis.

Testing was conducted in two cycles. Cycle I consisted of complete testing of the chassis using back-to-back testing techniques, failure determination, repair, and subsequent return to storage. Cycle II consisted of a duplication of this sequence after approximately 6 months of storage following Cycle I.

4. Parts

A total of 1,356 parts, previously involved in various Martin Marietta programs prior to a storage period, were retested for parameter degradation due to storage. The parts included resistors, capacitors, diodes, transistors, and integrated circuits. Each part was individually packaged and stored on shelves under controlled humidity and temperature (laboratory) conditions for approximately 1 year.

Individual part testing was conducted in two cycles. Cycle I defined the first sequence of tests performed on all parts. Cycle II followed failure determination and analysis and duplicated the procedure of Cycle I.

5. Ultrasonically Cleaned Printed Circuit Boards

The source of these items originated over 3 years ago when 75 shift-register printed circuit boards were evaluation tested at periodic intervals after having been subjected to ultrasonic cleaning. A test tool was fabricated at that time to permit measurement of all parameters of the individual parts which make up the board circuit. At termination of this test program, all boards were placed in storage under controlled humidity and temperature (laboratory) conditions. These printed circuit parts were again retested, this time for the effects of storage, utilizing the test tool and procedure previously used.

This testing was conducted in two cycles. Cycle I provided complete test, failure determination, and failure analysis of all parts which make up the circuitry of these boards. Cycle II was a duplication of this procedure at the conclusion of a 6 month storage period.

6. Micromodules

A total of 1,506 micromodules from prior tests, designed to determine whether they would function properly when exposed to selected environments, were used for storage tests. The modules had been stored in a semitropical environment for approximately 6 months prior to Phase I. Testing was conducted using a specially designed automatic test set which supplied the necessary power sources and equipment indicators to verify proper operation of the modules.

During Phase I, micromodule testing was conducted in two cycles. Cycle I defined the first sequence of tests performed. Cycle II followed failure determination and analysis and duplicated the procedure of Cycle I.

Following a storage period of approximately 7 months these items underwent a third sequence of tests (Phase II) which duplicated the tests performed in Phase I (previously referred to as Cycle I and Cycle II in Reference 58).

Manufactured by Martin Marietta, these micromodules are in the form of a cube that measures 0.600 ± 0.010 inch and weights approximately 0.016 pound.

The following modules or elements which contain microcircuits or discrete parts, or both, were included in the test program.

a. Input Converter Assembly

Each element contains 4 microcircuit two-input gates, 4 diodes, and 12 resistors. It converts incoming negative 12 volt logic to positive 3 volt logic. Eighty-eight input converter micromodules were available from storage for test.

b. Output Converter

Each element contains 2 microcircuit two-input gates, 2 transistors, 4 diodes, and 6 resistors. Each of the two-input gates is designed to convert positive 3 volt logic to negative 12 volt logic. One hundred forty-three of these micromodules were available for test.

c. Driver "D"

Each element contains 3 microcircuit three-input NOR gates, 1 microcircuit three-input lamp driver, and 3 resistors. This module is used to operate 12 volt relay coils or indicator lamps with 3 volt logic inputs. Sixty-eight of these items were available.

d. Half Adder

Each element contains 2 half adder microcircuits. This item is used with complemented inputs to perform the half adder function. Three hundred eighteen of these modules were available for test.

e. Gate "G" Modules

Each element contains 3 microcircuit three-input NOR gates which performs the logic function $Z = a + b + c = a \cdot b \cdot c$. Six hundred ninety-two of these items were available from storage for test.

f. Column Switch "CS"

Each element contains 5 capacitors which are used in conjunction with a single shot module to obtain 0.48, 1, 2, 4, and 8 millisecond pulse-widths. Thirty-three of these elements were available for testing.

g. Relay "R"

Each element contains 2 double pole, double throw relays. Each relay has 2 normally closed contacts capable of switching a 1 ampere signal at 28 Vdc. Each relay coil has a diode across the coil to provide transient suppression. One hundred fifteen of these items were available for test.

7. Test Console Parts

A total of 584 parts consisting of transistors and diodes were removed from stored test consoles and tested for the effects of storage. These parts had been in storage for approximately 26 months.

The test console parts tests were conducted in two cycles. Cycle I defines the first sequence of tests performed. Cycle II began following failure determination and analysis.

8. Individual Monolithic Microcircuits

A total of 165 microcircuits were stored under controlled humidity and temperature (laboratory) conditions. All of these samples were tested for catastrophic storage effects during Phase I and Phase II of the contract.

The Phase I storage period consisted of 11 months and Phase II was 9 months. All devices produced by different manufacturers were identified by a distinct code.

## B. DRIFT ANALYSIS

Data analysis of hardware types 1 through 7 (Table I) are contained in section 4 of Reference 58.

Table II lists the different types of microcircuits analyzed, the manufacturer code, the quantity in each group, and the general drift tendencies of the parameters measured. The grand average of Table II represents the arithmetic mean of the total parameter measurements recorded corresponding to their respective specification limits. Only 56 microcircuits had been tested prior to being placed in storage for Phase I; therefore, the drift analysis is devoted exclusively to these units.

The drift rate per month reflects the rate calculated by fitting a regression line to the three data points recorded during storage. The rates given do not reflect any adjustment for test equipment error which could have some effect upon the readings. Since the typical test equipment used could not have contributed more than 0.01 percent error to each mean measurement, this effect on drift rate would appear to be minor. However, when using the drift rates, they are meant only as a preliminary guide toward general drift tendencies.

The results of this analysis indicate that some parameters can vary erratically during storage and still remain in specification, while others tend to drift consistently in one direction.

Input turn-off current appears to increase or remain about the same rather than decrease. Although output level-off voltage has a negative drift rate on both gates and flip-flops, it appears to be erratic in nature.

Microcircuit parameters tend to vary irregularly during storage. If data could be accumulated over a longer period of time with frequent readings taken, a more definite drift trend might become apparent.

TABLE II

Microcircuit Drift Analysis Summary

| Identification | Number Analyzed | Manufacturer | Parameter Measured | Specification Limits | Grand Average: Average Storage Between Tests: 11 Months — Mean No. 1 | Mean No. 2 | Grand Average: Average Storage Between Tests: 9 Months — Mean No. 3 | Drift Rate Per Month |
|---|---|---|---|---|---|---|---|---|
| DTL binary element flip-flop | 8 | K (1964) | Output level-off voltage | ≥2.5V | 4.76 | 4.90 | 3.98 | -0.038 |
| | | | Output level-on voltage | ≤0.6V | 0.27 | 0.27 | 0.27 | 0.000 |
| | | | Direct set-reset Inputs, up current | ≤0.25 μa | 0.016 | 0.017 | 0.018 | 0.000 |
| DTL line driver gate | 10 | K (1964) | Input turn-off current | ≤3.75 ma | 2.87 | 3.11 | 3.02 | +0.008 |
| | | | Input leakage current | ≤0.25 μa | 0.0122 | 0.0457 | 0.0196 | +0.0004 |
| | | | Output level-off voltage | ≥2.0V | 2.39 | 1.76 | 2.28 | -0.007 |
| | | | Output saturation voltage | ≤0.6V | 0.34 | 0.32 | 0.32 | -0.001 |
| DTL dual gate | 7 | L (1964) | Input diode leakage | ≤0.10 ua | 0.021 | 0.047 | 0.023 | +0.001 |
| | | | Output saturation voltage | ≤1.0V | 0.90 | 0.90 | 0.91 | 0.000 |
| Dual NAND/NOR line driver gate | 5 | L (1964) | Output turn-off current | ≥4.7V | 4.84 | 4.81 | 4.90 | +0.003 |
| | | | Input diode leakage | ≤0.10 ua | 0.014 | 0.040 | 0.014 | +0.0001 |
| | | | Output saturation voltage | ≤1.0V | 0.84 | 0.88 | 0.84 | +0.0002 |
| NAND/NOR gate | 5 | D (1964) | Voltage off | ≥1.7V | 3.04 | 3.38 | 3.12 | +0.004 |
| | | | Voltage on | ≤0.3V | 0.026 | 0.026 | 0.012 | -0.0006 |
| DTL dual NAND gate | 9 | J (1964) | Input diode leakage | ≤0.10 ua | 0.006 | 0.019 | 0.003 | -0.0001 |
| | | | Output saturation voltage | ≤0.45V | 0.390 | 0.384 | 0.382 | -0.0004 |
| DTL dual NAND line driver | 12 | J (1964) | Turn-off voltage | ≥1.8V | 4.88 | 5.00 | 4.81 | +0.003 |
| | | | Output saturation | ≤0.45V | 0.424 | 0.410 | 0.440 | +0.001 |

# SECTION 4

# FAILURE RATES AND FACTORS

## A. INTRODUCTION

In compiling the part data for analysis, it was necessary to group these data by part classification and by mode (storage or dormancy) within each part classification. Because microcircuits are of major interest, these have been discussed separately in addition to being grouped within their normal part classification. The classifications used for this data grouping are listed and described in Table III.

Table IV shows the quantity of raw data available by part classification at the present time. This report presents the resultant failure rates and factors for which data are available (Table IV). Where sufficient data are not available within a part classification, the resultant failure rates and factors are reported as not currently available.

Generally, the nonoperating experience in part-hours and failure information have been logically combined to calculate the dormant operating and the storage failure rates shown in this chapter. All of these data have been evaluated to the lowest level possible (part type or subtype) within each part classification. The reported experience in part-hours for certain part types may exceed the sum of the subtypes which comprise that class. This is because data collected were only identified to the part type level and not the part subtype level.

In addition, some data have been collected which indicate the type of failure, i.e., catastrophic and drift. Catastrophic failures are defined as a change in the characteristics of a part resulting in a complete lack of useful performance of that part. A drift failure is any change in a particular parameter such that the resulting parameter measurement is not within the parameter range requirements stipulated in the governing specification or document.

Failure rates on components and electronic assemblies, such as printed circuit boards and chassis, were reported in Reference 58. Since no

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TABLE III

Description of Electronic Part Classifications

| Part Classification | Associated Testing and Screening | Typical Using Project |
| --- | --- | --- |
| 1 Commercial | None | |
| 2 Military standard | Group A Environmental proof tests + Group B electrical tests | Pershing |
| 3 Selected military standard | Class 2 + selected vendor + serializing + 100% receiving inspection + burn-in | Sprint |
| 4 High reliability | Class 3 except 100% burn-in and screens with associated study program. | Minuteman |

## TABLE IV

Quantity of Dormant Operating and Storage Data Available
By Part Classification

| Part Classification | Raw Data Collected ~ Part Hours x $10^6$ | |
|---|---|---|
| | Storage | Dormant Operation |
| Commercial | 33.8778 | 0.0 |
| Military standard | 76,179.9388 | 64.7727 |
| Select military standard | 52,440.2120 | 24.2204 |
| High reliability | 189,904.8608 | 441,595.9536 |
| Sub Total | 318,558.8894 | 441,684.9467 |
| Grand Total | 760,243.8361 | |

additional data have been collected on components, the earlier listing is not repeated herein.

1. Commercial Part Class

All of the 33 million part-hours of data collected on commercial parts are in the storage mode. The quantity of data is very limited. No catastrophic failures and some drift failures have been observed to date. As a result, only limiting values for failure rates can be determined. These are shown in Table V.

2. Military Standard Part Class

Over 76 billion part-hours of data have been amassed on military standard parts in the storage mode. In the case of high usage parts, sufficient data have been collected to permit determination of the high usage part failure rates. With low usage parts, a collection of additional part-hours of experience is still needed. Table VI reflects the storage failure rates on military standard parts.

Over 64 million part-hours of experience have been collected in the dormant operating mode. No drift and six catastrophic failures have been observed to date and as a result, mostly limiting values for failure rates can be established. These are shown in Table VII.

3. Selected Military Standard Part Class

Over 52 billion part-hours of data have been accumulated on this class of parts in the storage mode. Some high usage parts have sufficient storage experience so that failure rates can be established. The remaining selected military standard parts require additional part-hours of experience to accurately establish their associated failure rates. Table VIII reflects the storage failure rates on this class of parts.

In the dormant operating mode, over 24 million part-hours of data have been collected. Two failures have been observed to date. The resulting dormant operating failure rates for selected military standard parts are listed in Table IX.

4. High Reliability Part Class

Over 189 billion part-hours of data have been amassed on high reliability parts in the storage mode. This experience is all on electronic parts, and none on electromechanical parts. In addition, only catastrophic failures have been reported. The resulting catastrophic storage failure rates on high reliability parts are shown in Table X.

## TABLE V

Observed Storage Part Failure Rates, Commercial Parts

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Bearings, ball, annular | 0.4234 | 0 | < 2360 | 2 | 4720 |
| Boards, terminal | 0.2701 | 0 | < 3700 | 0 | < 3700 |
| Cables | | | | | |
| Battery | 1.2702 | 0 | < 788 | 11 | 8660 |
| Harness | 0.2117 | 0 | < 4730 | 0 | < 4730 |
| Commutators (subassembly) | 0.3336 | 0 | < 3000 | 0 | < 3000 |
| Connections, one, solder | 12.7020 | 0 | < 78.8 | 0 | < 78.8 |
| Connectors, panel and receptacle | 8.8920 | 0 | < 113* | 0 | < 113* |
| Driveshafts, propeller | 0.2628 | 0 | < 3810 | 0 | < 3810 |
| Fins, steering | 0.2300 | 0 | < 4350 | 0 | < 4350 |
| Gaskets, fiber | 2.9200 | 0 | < 340 | 11 | 3770 |
| Inertial guidance devices | | | | | |
| Gimbal centers | 0.2446 | 0 | < 4090 | 0 | < 4090 |
| Lugs, terminal, solder | 3.8110 | 0 | < 263 | 0 | < 263 |
| Relays | 0.9841 | 0 | < 1020 | 5 | 5080 |
| Springs, coil | 0.4536 | 0 | < 2210 | 0 | < 2210 |
| Switch, pressure (bellows) | 0.6132 | 0 | < 1630 | 4 | 6520 |
| Timers, thermal | 0.2555 | 0 | < 3920 | 0 | < 3920 |
| Valves, air | 0.6358 | 0 | < 1570 | 0 | < 1570 |

*Per pin socket connection

TABLE VI

Observed Storage Part Failure Rates, Military Standard Parts

| | Experience Part-Hours (X10$^6$) | Catastrophic Failures | Catastrophic λ Fits | Drift Failures | Drift λ Fits |
|---|---|---|---|---|---|
| Antennas | 1.9612 | 0 | < 510 | 0 | < 510 |
| Batteries | 13.0274 | 61 | 4682 | 0 | < 76.8 |
| Silver zinc primary | 11.7200 | 61 | 5200 | 0 | < 85.3 |
| Bulbs | 9.6720 | 0 | < 103 | 0 | < 103 |
| Neon | 9.6720 | 0 | < 103 | 0 | < 103 |
| Capacitors | 12,477.6336 | 26 | 2.1 | 9 | 0.7 |
| Ceramic | 1,024.4857 | 0 | < 1.0 | 1 | 1.0 |
| Electrolytic | 65.1045 | 0 | < 15.4 | 0 | < 15.4 |
| Foil Mylar | 7.6211 | 0 | < 131 | 0 | < 131 |
| Glass | 799.3428 | 0 | < 1.3 | 2 | 2.5 |
| Metallized Mylar | 4.4656 | 0 | < 224 | 0 | < 224 |
| Mica | 208.7418 | 2 | 9.5 | 0 | < 4.8 |
| Paper (includes oil paper) | 995.2449 | 3 | 3.0 | 2 | 2.0 |
| Paper foil film (includes paper Mylar) | 7.4488 | 0 | < 134 | 0 | < 134 |
| Plastic (includes plastic dielectric and polystrene foil) | 19.4273 | 0 | < 51.5 | 0 | < 51.5 |
| Porcelain | 48.6950 | 0 | < 20.5 | 0 | < 20.5 |
| Tantalum (includes tantalum electrolytic) | 15.9678 | 0 | < 63.0 | 0 | < 63.0 |
| Tantalum foil wet | 240.9026 | 1 | 4.2 | 0 | < 4.2 |
| Tantalum slug wet (includes tantalum sintered wet) | 59.6220 | 4 | 67.1 | 0 | < 16.8 |
| Tantalum solid | 22.5104 | 1 | 44.4 | 0 | < 44.4 |
| Variable, air | 1.3526 | 0 | < 739 | 0 | < 739 |
| Variable, ceramic | 2.7053 | 0 | < 370 | 0 | < 370 |
| Variable, glass | 15.8606 | 0 | < 63 | 0 | < 63 |

Table VI (Cont)

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Choppers | 1.7647 | 0 | < 567 | 0 | < 567 |
| Connectors | 396.6799 | 2 | 5.0 | 0 | < 2.5 |
| Soldered (average 20 pins) | 169.2600 | 0 | < 5.9 | 0 | < 5.9 |
| Contact, stainless steel (welded) | 227.4199 | 2 | 8.8 | 0 | < 4.4 |
| Crystals | 8.5434 | 1 | 117 | 0 | < 117 |
| Dividers, power | 0.6537 | 0 | < 1530 | 0 | < 1530 |
| Explosive devices | 3.9512 | 1 | 253 | 0 | < 253 |
| Detonators | 1.3074 | 0 | < 765 | 0 | < 765 |
| Ignitors | 1.9008 | 0 | < 526 | 0 | < 526 |
| Squibs | 0.7430 | 1 | 1346 | 0 | < 1346 |
| Inductive devices | | | | | |
| Coils | 761.1664 | 1 | 1.3 | 0 | < 1.3 |
| Filter regulator | 0.7398 | 0 | < 1352 | 0 | < 1352 |
| Magnetic | 362.5560 | 0 | < 2.8 | 0 | < 2.8 |
| Power | 14.8779 | 1 | 67.2 | 0 | < 67.2 |
| Radio frequency | 392.6616 | 0 | < 2.5 | 0 | < 2.5 |
| Filters | 15.5516 | 1 | 64.3 | 0 | < 64.3 |
| Assembly | 2.2320 | 1 | 448 | 0 | < 448 |
| Radio frequency | 12.6659 | 0 | < 79 | 0 | < 79 |
| Reactors, inductors and chokes | 122.4963 | 0 | < 8.2 | 0 | < 8.2 |
| Audio frequency | 7.9700 | 0 | < 125 | 0 | < 125 |
| Individual windings | 2.2320 | 0 | < 448 | 0 | < 448 |
| Radio frequency | 3.5420 | 0 | < 282 | 0 | < 282 |
| Saturated | 0.3699 | 0 | < 2700 | 0 | < 2700 |
| Toroidal | 9.6720 | 0 | < 103 | 0 | < 103 |
| Solenoids (includes rotary switches and solenoid relays | 3.5267 | 0 | < 284 | 0 | < 284 |

Table VI (Cont)

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Instruments | 147.3000 | 25 | 170 | 0 | < 6.8 |
| Inertial guidance devices | 39.1269 | 14 | 358 | 3 | 76.7 |
| Accelerometer | 9.6720 | 0 | < 103 | 0 | < 103 |
| Gyros, electromechanical | 28.1023 | 11 | 391 | 0 | < 35.6 |
| Gyros, springwound | 1.3526 | 3 | 2217 | 3 | 2217 |
| Micromodules | 303.4793 | 6 | 19.8 | 0 | < 3.3 |
| Microwave devices | 2.7053 | 0 | < 370 | 0 | < 370 |
| Cavities | 2.7053 | 0 | < 370 | 0 | < 370 |
| Mixers | 0.6537 | 0 | < 1530 | 0 | < 1530 |
| Relays | 682.1186 | 40 | 58.6 | 1 | 1.5 |
| Armature | 148.4432 | 20 | 135 | 0 | < 6.7 |
| Crystal can | 38.8041 | 0 | < 25.8 | 0 | < 25.8 |
| 1/2 size crystal can | 4.6659 | 0 | < 214 | 0 | < 214 |
| Microminiature | 0.1168 | 0 | < 8562 | 0 | < 8562 |
| Miniature | 0.7244 | 0 | < 1380 | 0 | < 1380 |
| Rotary | 0.1640 | 0 | < 6098 | 0 | < 6098 |
| Resistors | 34,895.3640 | 30 | 0.9 | 85 | 2.4 |
| Fixed | 12,911.9320 | 14 | 1.1 | 59 | 4.6 |
| Carbon composition | 9,391.4857 | 1 | 0.1 | 33 | 3.5 |
| Film | 2,684.0719 | 11 | 4.1 | 24 | 9.0 |
| Carbon | 1,918.4395 | 11 | 5.7 | 24 | 12.5 |
| Metal | 719.0235 | 0 | < 1.4 | 0 | < 1.4 |
| Thermistors | 7.2708 | 0 | < 138 | 0 | < 138 |
| Wirewound | 829.1036 | 2 | 2.4 | 2 | 2.4 |
| Power | 237.7293 | 0 | < 4.2 | 2 | 8.5 |
| Precision | 276.0810 | 1 | 3.6 | 0 | < 3.6 |
| Variable | 424.2643 | 2 | 4.7 | 4 | 9.5 |
| Carbon composition | 121.6828 | 0 | < 8.2 | 2 | 16.4 |

Table VI (Cont)

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failure | λ Fits | Failure | λ Fits |
| Linear precision | 2.9593 | 0 | < 338 | 1 | 338 |
| Wirewound (includes trimmers) | 212.7805 | 1 | 4.7 | 1 | 4.7 |
| Potentiometers | 76.4842 | 0 | < 13.1 | 0 | < 13.1 |
| Rotary electrical devices | 127.3384 | 0 | < 7.8 | 0 | < 7.8 |
| Generators | 4.8360 | 0 | < 207 | 0 | < 207 |
| AC | 4.8360 | 0 | < 207 | 0 | < 207 |
| Motors | 60.1950 | 0 | < 16.6 | 0 | < 16.6 |
| AC (includes AC blowers) | 9.6720 | 0 | < 103 | 0 | < 103 |
| DC | 44.2360 | 0 | < 22.6 | 0 | < 22.6 |
| Gage pot | 0.6537 | 0 | < 1530 | 0 | < 1530 |
| Rotors | 62.3074 | 0 | < 16.0 | 0 | < 16.0 |
| Semiconductors | | | | | |
| Diodes | 19,357.6736 | 60 | 3.1 | 5 | 0.3 |
| High-power rectifier (Si) | 81.1450 | 0 | < 12.3 | 0 | < 12.3 |
| High-power zener (Si) | 0.6898 | 0 | < 1450 | 0 | < 1450 |
| Medium-power rectifier (Si) | 100.5358 | 1 | 9.9 | 0 | < 9.9 |
| Medium-power zener (Si) | 9.5406 | 0 | < 105 | 0 | < 105 |
| Low-power rectifier (Si) | 11,712.1655 | 8 | 0.7 | 1 | 0.1 |
| Low-power rectifier (Ge) | 123.4998 | 2 | 16.2 | 0 | < 8.1 |
| Low-power zener (Si) | 1,279.0401 | 3 | 2.3 | 0 | < 0.8 |
| Low-power planar whisker (Si) | 0.1918 | 0 | < 5214 | 0 | < 5214 |
| Low-power planar Dbl slug (Si) | 0.0924 | 0 | < 10823 | 0 | < 10823 |
| Low-power microwave (Si) | 25.5326 | 0 | < 39.2 | 1 | 39.2 |
| Low-power mesa whiskerless (Si) | 29.2728 | 1 | 34.2 | 0 | < 34.2 |
| Low-power mesa (Si) | 1.2586 | 0 | < 794 | 0 | < 794 |
| Bridge assembly (4 encapsulated) | 212.7840 | 2 | 9.4 | 0 | < 4.7 |
| Special silicon, SU3430 and SU3431 | 32.5750 | 1 | 30.7 | 0 | < 30.7 |

Table VI (Cont)

| | Experience Part-Hours ($X10^6$) | Catastrophic Failure | Catastrophic λ Fits | Drift Failure | Drift λ Fits |
|---|---|---|---|---|---|
| Microcircuits | 1,392.7427 | 32 | 23.0 | 2 | 1.4 |
| DCTL | 15.4953 | 2 | 129 | 0 | < 64.5 |
| DTL | 119.3388 | 6 | 50.3 | 0 | < 8.4 |
| MECL | 0.6699 | 1 | 1492 | 0 | < 1492 |
| RCTL | 0.0354 | 0 | < 28300 | 0 | < 28300 |
| RTL | 1,205.2043 | 21 | 17.4 | 1 | 0.8 |
| Silicon controlled rectifiers | 4.8360 | 0 | < 207 | 0 | < 207 |
| High-power planar | 4.8360 | 0 | < 207 | 0 | < 207 |
| Silicon controlled switches | 0.2660 | 0 | < 3759 | 0 | < 3759 |
| Transistors | 3,742.9964 | 68 | 18.2 | 52 | 13.9 |
| High-power alloy (Si) | 61.7957 | 1 | 16.2 | 4 | 64.7 |
| High-power alloy (Ge) | 5.5758 | 0 | < 179 | 0 | < 179 |
| High-power mesa (Si) | 26.2819 | 4 | 152 | 0 | < 38.0 |
| Medium-power alloy (Si) | 10.8165 | 0 | < 92.4 | 0 | < 92.4 |
| Medium-power mesa (Si) | 325.7183 | 1 | 3.1 | 2 | 6.1 |
| Medium-power planar (Si) | 311.7927 | 0 | < 3.2 | 0 | < 3.2 |
| Medium-power planar (Ge) | 2.5691 | 0 | < 389 | 0 | < 389 |
| Low-power alloy (Si) | 133.4865 | 10 | 74.9 | 0 | < 7.5 |
| Low-power alloy (Ge) | 1,117.9947 | 30 | 26.8 | 40 | 35.8 |
| Low-power mesa (Si) | 36.0391 | 1 | 27.7 | 0 | < 27.7 |
| Low-power planar (Si) | 167.0079 | 4 | 24.0 | 0 | < 6.0 |
| Low-power planar (Ge) | 1.2280 | 0 | < 814 | 0 | < 814 |
| Unijunction | 4.3236 | 0 | < 231 | 0 | < 231 |
| Field Effect | 2.8389 | 0 | < 352 | - | -* |
| Switches | 118.1556 | 21 | 178 | 0 | < 8.5 |
| Acceleration | 0.6537 | 0 | < 1530 | 0 | < 1530 |
| Pressure | 31.0010 | 10 | 323 | 0 | < 32.3 |
| Push | 0.9678 | 0 | < 1033 | 0 | < 1033 |

*No data

Table VI (Cont)

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failure | λ Fits | Failure | λ Fits |
| Sensitive | 0.3669 | 0 | < 2730 | 0 | < 2730 |
| Rotary | 1.1097 | 0 | < 901 | 0 | < 901 |
| Toggle | 8.9260 | 0 | < 112 | 0 | < 112 |
| Inertial | 25.3370 | 6 | 237 | 0 | < 39.5 |
| Timers (includes time delay relays) | 8.5840 | 0 | < 116 | 0 | < 116 |
| Thermal (includes thermostatic switches) | 4.3340 | 0 | < 231 | 0 | < 231 |
| Electronic | 1.3800 | 0 | < 725 | 0 | < 725 |
| Transformers | 718.7386 | 10 | 13.9 | 3 | 4.2 |
| High power | 17.3598 | 0 | < 57.6 | 0 | < 57.6 |
| Current | 0.1968 | 0 | < 5081 | 0 | < 5081 |
| Isolation | 0.0328 | 0 | < 30488 | 0 | < 30488 |
| Power | 16.9805 | 0 | < 58.9 | 0 | < 58.9 |
| Synchro control | 0.1497 | 0 | < 6680 | 0 | < 6680 |
| Low power | 160.9800 | 0 | < 6.2 | 0 | < 6.2 |
| Audio | 117.9571 | 0 | < 8.5 | 0 | < 8.5 |
| Pulse | 37.6123 | 0 | < 26.6 | 0 | < 26.6 |
| Radio | 5.4106 | 0 | < 184 | 0 | < 184 |
| Tubes | 792.2156 | 15 | 18.9 | 5 | 6.3 |
| Electron | 639.7341 | 10 | 15.6 | 4 | 6.3 |
| Reflex Klystron | 4.8360 | 0 | < 207 | 0 | < 207 |
| Valves | 29.0160 | 2 | 68.9 | 0 | < 34.5 |
| Servo | 29.0160 | 2 | 68.9 | 0 | < 34.5 |

TABLE VII

Observed Dormant Operating Failure Rates,
Military Standard Parts

| | Experience Part-Hours ($X10^6$) | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Semiconductors | | | | | |
| Microcircuits | 66.0777 | 6 | 90.8 | 0 | < 15.7 |
| DCTL | 8.0340 | 0 | < 126 | 0 | < 126 |
| DTL | 8.8124 | 0 | < 114 | 0 | < 114 |
| MECL | 18.3652 | 0 | < 54.5 | 0 | < 54.5 |
| RTL | 6.0625 | 0 | < 165 | 0 | < 165 |
| TTL | 3.6076 | 0 | < 277 | 0 | < 277 |
| Transistors | 1.1792 | 0 | < 848 | 0 | < 848 |
| Field effect, junction | 1.1792 | 0 | < 848 | 0 | < 848 |

TABLE VIII

Observed Storage Part Failure Rates,
Selected Military Standard Parts

| | Experience | Catastrophic | | Drift* | |
|---|---|---|---|---|---|
| | Part-Hours ($X10^6$) | Failures | λ Fits | Failures | λ Fits |
| Capacitors | 702.3229 | 0 | < 1.42 | | |
| Ceramic | 133.5976 | 0 | < 7.49 | | |
| Foil Mylar | 80.8040 | 0 | < 12.4 | | |
| Glass | 6.1584 | 0 | < 162 | | |
| Metallized Mylar | 20.0270 | 0 | < 49.9 | | |
| Mica | 26.3331 | 0 | < 38.0 | | |
| Paper metallized | 78.3373 | 0 | < 12.8 | | |
| Plastic (includes plastic dielectric and polystrene foil) | 8.0955 | 0 | < 124 | | |
| Tantalum foil wet | 16.2072 | 0 | < 61.7 | | |
| Tantalum slug wet | 56.5730 | 0 | < 17.7 | | |
| Tantalum solid | 138.1941 | 0 | < 7.24 | | |
| Variable, air | 1.7976 | 0 | < 556 | | |
| Variable, ceramic | 0.5243 | 0 | < 1910 | | |
| Connectors | 36.4662 | 0 | < 27.4 | | |
| Connections | 6,055.6686 | 0 | < 0.17 | | |
| Soldered | 6,055.6686 | 0 | < 0.17 | | |
| Crystals | 0.0230 | 0 | < 43,500 | | |
| Explosive devices | 919.0030 | 35 | 38.1 | | |
| Actuators | 31.2600 | 8 | 256 | | |
| Bellows | 10.6270 | 1 | 94 | | |
| Bolts | 1.8330 | 10 | 5456 | | |

*Not currently available

TABLE VIII (cont)

| | Experience Part Hours ($X10^6$) | Catastrophic | | Drift* | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Motors | 42.4130 | 0 | < 23.6 | | |
| Squibs | 620.0000 | 14 | 22.6 | | |
| Switches | 206.3950 | 2 | 9.7 | | |
| Timers | 6.4750 | 0 | < 154 | | |
| Inductive devices | 23.7790 | 0 | < 42.1 | | |
| Coils | 17.4720 | 0 | < 57.2 | | |
| Reactors, inductors and chokes | 6.3070 | 0 | < 159 | | |
| Radars | 14.3510 | 9 | 627 | | |
| Proximity fuse type | 14.3510 | 9 | 627 | | |
| Relays | 36.7824 | 0 | < 27.2 | | |
| Resistors | 1,924.9335 | 3 | 1.56 | | |
| Carbon composition | 1,358.7328 | 0 | < 0.74 | | |
| Film | 182.4305 | 0 | < 5.48 | | |
| Thermistors | 12.2014 | 0 | < 82.0 | | |
| Wirewound | 60.7510 | 0 | < 16.5 | | |
| Power | 26.6509 | 0 | < 37.5 | | |
| Precision | 33.0885 | 0 | < 30.2 | | |
| Stripline | 0.1498 | 0 | < 6670 | | |
| Semiconductors | | | | | |
| Diodes | 37,714.4762 | 43 | 1.14 | | |
| High-power rectifier (Si) | 50.4305 | 0 | < 19.8 | | |
| High-power Zener (Si) | 4.0518 | 0 | < 247 | | |
| Medium-power rectifier (Si) | 259:2610 | 0 | < 3.86 | | |
| Medium-power Zener (Si) | 19.4450 | 0 | < 51.4 | | |
| Low-power rectifier (Si) | 6,415.2089 | 3 | 0.47 | | |
| Low-power Zener (Si) | 1,196.3436 | 5 | 4.18 | | |

*Not currently available

TABLE VIII (Cont)

| | Experience Part Hours ($X10^6$) | Catastrophic | | Drift* | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | Fits |
| General, Zener | 1,268.3590 | 12 | 9.46 | | |
| General | 28,501.3760 | 23 | 0.81 | | |
| Transistors | 4,783.4697 | 35 | 7.32 | | |
| High-power (Si) | 62.3422 | 0 | < 16.0 | | |
| Medium-power (Si) | 956.1563 | 2 | 2.09 | | |
| Low-power (Ge) | 8.1036 | 0 | < 123 | | |
| Low-power (Si) | 1,109.2804 | 13 | 11.7 | | |
| Unijunction | 4.9112 | 0 | < 204 | | |
| General | 2,605.6760 | 20 | 7.68 | | |
| Silicon controlled rectifiers | 58.2175 | 0 | < 17.2 | | |
| High-power | 12.0162 | 0 | < 83.2 | | |
| Medium power | 32.1824 | 0 | < 31.1 | | |
| Low power | 14.0189 | 0 | < 71.3 | | |
| Spark gaps | 53.0000 | 0 | < 18.9 | | |
| Switches | 0.6240 | 0 | < 1600 | | |
| Timers (includes time delay relays) | 30.5227 | 8 | 262 | | |
| Motor driven | 21.4709 | 8 | 373 | | |
| Interval (includes interval switches) | 3.3479 | 5 | 1493 | | |
| Sequential | 18.1230 | 3 | 166 | | |
| Transformers | 85.2396 | 0 | < 11.7 | | |
| High power | 0.0847 | 0 | < 11,800 | | |
| Power | 0.0847 | 0 | < 11,800 | | |
| Low power | 0.3376 | 0 | < 2960 | | |
| Audio | 0.2529 | 0 | < 3950 | | |
| Pulse | 0.0847 | 0 | < 11,800 | | |
| Tubes | 1.3325 | 5 | 3,750 | | |
| Krytron | 0.0847 | 0 | < 11,800 | | |
| Magnatron | 0.6240 | 4 | 6410 | | |
| Traveling wave | 0.6240 | 1 | 1603 | | |

*Not currently available

# TABLE IX

## Observed Dormant Operating Part Failure Rates, Selected Military Standard Parts

| | Experience | Catastrophic | | Drift | |
|---|---|---|---|---|---|
| | Part Hours ($X10^6$) | Failures | λ Fits | Failures | λ Fits |
| Capacitors | 1.6430 | 0 | < 610 | 0 | < 610 |
| Mica | 0.8750 | 0 | < 1140 | 0 | < 1140 |
| Paper | 0.5670 | 0 | < 1760 | 0 | < 1760 |
| Plastic (includes polystrene foil) | 0.1970 | 0 | < 5080 | 0 | < 5080 |
| Inductive devices | 0.9580 | 0 | < 1040 | 0 | < 1040 |
| Inductors, radio frequency | 0.9580 | 0 | < 1040 | 0 | < 1040 |
| Resistors | 1.1480 | 0 | < 871 | 0 | < 871 |
| Fixed | 1.1480 | 0 | < 871 | 0 | < 871 |
| Carbon composition | 0.2620 | 0 | < 3820 | 0 | < 3820 |
| Wirewound | 0.8860 | 0 | < 1130 | 0 | < 1130 |
| Power | 0.0490 | 0 | < 20400 | 0 | < 20400 |
| Precision | 0.8370 | 0 | < 1190 | 0 | < 1190 |
| Semiconductors | | | | | |
| Diodes | 3.1773 | 0 | < 315 | 0 | < 315 |
| High-power rectifier (Si) | 0.0045 | 0 | < 222000 | 0 | < 222000 |
| Medium-power rectifier (Si) | 0.0116 | 0 | < 86,200 | 0 | < 86,200 |
| Medium-power Zener (Si) | 0.0002 | 0 | < $5x10^6$ | 0 | < $5 \times 10^6$ |
| Low-power rectifier (Si) | 0.4511 | 0 | < 2200 | 0 | < 2200 |
| Low-power Zener (Si) | 0.0900 | 0 | < 11100 | 0 | < 11100 |
| General purpose | 2.4720 | 0 | < 404 | 0 | < 404 |
| General Zener | 0.1479 | 0 | < 6760 | 0 | < 6760 |
| Microcircuits | 16.7150 | 2 | 120 | 0 | < 26.4 |
| DTL | 2.4150 | 0 | < 414 | 0 | < 414 |
| RCTL | 5.6430 | 1 | 177 | 0 | < 177 |
| RTL | 8.6570 | 1 | 116 | 0 | < 116 |
| Transistors | 0.4581 | 0 | < 2180 | 0 | < 2180 |
| High-power | 0.0068 | 0 | < 147,000 | 0 | < 147,000 |
| Medium-power | 0.0663 | 0 | < 15,100 | 0 | < 15,100 |
| Low-power | 0.0819 | 0 | < 12,200 | 0 | < 12,200 |
| General | 0.3031 | 0 | < 3300 | 0 | < 3300 |
| Transformers | 0.1210 | 0 | < 8260 | 0 | < 8260 |
| Low power | 0.1210 | 0 | < 8260 | 0 | < 8260 |
| Radio | 0.1210 | 0 | < 8260 | 0 | < 8260 |

## TABLE X

Observed Storage Part Failure Rates,
High Reliability Parts

| | Experience Part Hours ($X10^6$) | Catastrophic Failures | Catastrophic λ Fits | Drift* Failures | Drift* λ Fits |
|---|---|---|---|---|---|
| Capacitors | 14,125.3310 | 1 | 0.07 | | |
| Glass | 5,293.8739 | 0 | < 0.19 | | |
| Paper | 2,056.2981 | 0 | < 0.49 | | |
| Tantalum foil wet | 1,667.5400 | 0 | < 0.59 | | |
| Tantalum solid | 5,087.6190 | 1 | 0.20 | | |
| Resistors | 91,583.2414 | 6 | 0.07 | | |
| Fixed | 91,583.2414 | 6 | 0.07 | | |
| Carbon composition | 85,095.7898 | 3 | 0.04 | | |
| Film | 3,956.1426 | 3 | 0.76 | | |
| Carbon | 931.2714 | 3 | 3.22 | | |
| Metal | 3,024.8712 | 0 | < 0.33 | | |
| Wirewound | 2,531.3090 | 0 | < 0.40 | | |
| Power | 2,062.5482 | 0 | < 0.48 | | |
| Precision | 468.7608 | 0 | < 2.13 | | |
| Semiconductors | | | | | |
| Diodes | 54,671.0717 | 27 | 0.49 | | |
| High power rectifier (Si) | 1,113.8415 | 0 | < 0.90 | | |
| Medium power general purpose (Si) | 2,481.3082 | 0 | < 0.40 | | |
| Medium power rectifier (Si) | 556.2632 | 0 | < 1.80 | | |
| Medium power zener (Si) | 243.7561 | 6 | 2.46 | | |
| Low power rectifier (Si) | 48,190.3681 | 14 | 0.29 | | |
| Low power rectifier (Ge) | 0.4208 | 0 | < 2375 | | |
| Low power zener (Si) | 2,085.1138 | 7 | 3.36 | | |
| Transistors | 29,525.2167 | 40 | 1.35 | | |
| High power (Si) | 1.2887 | 0 | < 776 | | |
| High power alloy (Ge) | 756.2676 | 5 | 6.61 | | |
| Medium power (Si) | 1.3150 | 0 | < 760 | | |
| Low power (Si) | 20,581.7338 | 12 | 0.58 | | |
| Low power (Ge) | 8,184.6116 | 23 | 2.81 | | |

*Not currently available

## TABLE XI

### Observed Dormant Operating Part Failure Rates, High Reliability Parts

| | Experience Part Hours (X10⁶) | Catastrophic | | Drifts* | |
|---|---|---|---|---|---|
| | | Failures | λ Fits | Failures | λ Fits |
| Capacitors | 37,894.8072 | 25 | 0.66 | | |
| Ceramic | 367.8716 | 0 | < 2.72 | | |
| Glass | 13,227.0501 | 1 | 0.08 | | |
| Mica | 879.0000 | 0 | < 1.14 | | |
| Paper | 5,704.5858 | 0 | < 0.18 | | |
| Paper foil film | 12.2343 | 0 | < 81.7 | | |
| Plastic | 210.0780 | 0 | < 4.76 | | |
| Tantalum foil wet | 4,202.3437 | 2 | 0.48 | | |
| Tantalum slug wet | 203.7637 | 14 | 68.7 | | |
| Tantalum solid | 12,687.5244 | 8 | 0.63 | | |
| Tantalum solid, polarized | 147.2330 | 0 | < 6.79 | | |
| Inductive device, inductor RF | 958.0000 | 0 | < 1.04 | | |
| Resistors | 186,018.8092 | 33 | 0.18 | | |
| Fixed | 186,018.8092 | 33 | 0.18 | | |
| Carbon composition | 169,811.5285 | 15 | 0.09 | | |
| Film | 9,305.3103 | 13 | 1.40 | | |
| Carbon | 1,836.3026 | 11 | 5.99 | | |
| Metal | 7,458.4609 | 2 | 0.27 | | |
| Metal Grid | 10.5468 | 0 | < 94.8 | | |
| Thermistors | 1.2656 | 0 | < 790 | | |
| Wirewound | 6,900.7048 | 5 | 0.72 | | |
| Power | 786.4306 | 0 | < 1.27 | | |
| Precision | 2,066.8181 | 3 | 1.45 | | |
| Semiconductors | | | | | |
| Diodes | 154,669.3281 | 156 | 1.01 | | |
| High power rectifier (Si) | 3,125.8589 | 2 | 0. | | |
| Medium power rectifier (Si) | 1,629.5742 | 2 | 1.23 | | |
| Medium power zener (Si) | 641.7342 | 41 | 63.9 | | |
| Low power rectifier (Si) | 134,973.3625 | 57 | 0.42 | | |
| General purpose | 6,993.3886 | 3 | 0.43 | | |
| Low power zener (Si) | 6,024.3875 | 33 | 5.48 | | |
| Medium power micro | 102.0928 | 8 | 78.4 | | |
| Low power micro | 1,178.7075 | 10 | 8.48 | | |
| Gallium Arsenide | 0.4219 | 0 | < 2370 | | |
| Microcircuits | 1,345.3469 | 55 | 40.9 | | |
| DTL | 1,231.8636 | 49 | 39.8 | | |
| Linear | 113.4833 | 6 | 52.9 | | |
| Transistors | 60,682.6622 | 285 | 4.70 | | |
| High power (Si) | 99.9835 | 42 | 420 | | |
| High power alloy (Ge) | 1,393.1014 | 29 | 20.8 | | |
| Low power alloy (Ge) | 20,347.7304 | 111 | 5.45 | | |
| Low power (Si) | 37,610.8273 | 79 | 2.10 | | |

*Not currently available

In the dormant operating mode, more than 441 billion part-hours of data have been amassed on high reliability parts. This experience is primarily on electronic parts, and only catastrophic failures have been reported. Table XI lists the dormant operating failure rates for high reliability parts.

5. Microcircuits

a. Normal Temperatures (25°C)

Because of the current interest in microcircuits by both industry and government, a detailed discussion on the dormant operating and storage data on microcircuits is included.

Of the approximately 3 billion part-hours of data collected to date on this part type, about 2.8 billion are at normal (25°C) temperatures. The remaining data are at elevated temperatures. Table XII shows a source breakdown by approximate quantities and part class for the 2.8 billion part-hours of microcircuit data at normal temperatures.

Although nc military specifications are presently in existence for military standard and high reliability microcircuts, the data were classified in this manner according to the associated testing and screening described in Table III.

TABLE XII

Sources of Microcircuit and Dormant Operating Data for Normal Temperatures

| | Microcircuit Experience (25°C) Part-Hours ($X10^6$) | |
|---|---|---|
| Source | Storage Military Standard Class | Dormant Operating High Reliability Class |
| Vendor | | |
| Field | 118.7 | - |
| Laboratory | 65.9 | 39.5 |
| Sub total - Vendor | 184.6 | 39.5 |
| Non vendor | | |
| Field | 1166.6 | 1383.3 |
| Laboratory | 8.4 | - |
| Sub total - Non vendor | 1175.0 | 1383.3 |
| Total | 1359.6 | 1422.8 |

Tables XIII and XIV present catastrophic microcircuit failure rates by source (vendor or nonvendor) for storage and dormant operations, respectively.

The 25°C storage and dormant catastrophic failure rates of Tables XIII and XIV should be considered in the light of the best current operating experience data reported in the most current literature. References 51 to 56 and 61 to 68 best furnish current operating information and estimates.

b. Elevated Temperatures

Data on microcircuits have been collected and grouped by source of data (vendor and nonvendor) and by environment (field or laboratory) for both the storage and dormant operating modes. The total data available for temperature analysis is on microcircuits spanning the 1963 to 1966 time period and amounts to 2.99 billion part-hours of experience, of which vendor data comprises 0.39 billion and non vendor 2.60 billion. In only a few instances were storage drift failures reported; thus, any determination of drift failure rate variation with temperature had to be precluded from the following analysis.

1) Analysis of Storage Data

The determination of the catastrophic failure rate of microcircuits versus temperature begins with a critical review of both vendor and nonvendor storage data in order to derive meaningful information and to evaluate any apparent implications or anomalies. Table XV has been constructed to aid in this evaluation.

To investigate the possibility of true time acceleration and to assist in evaluating the differences between the vendor and nonvendor data, an analysis was made based upon the Arrhenius theory. The data from Table XV are plotted in Figure 1. The data utilized in constructing Figure 1 covers various microcircuit types of different vintages and under various field and laboratory environments. Figure 1 is not intended to provide data or test criteria on specific microcircuit device types, but is intended to indicate the average trend of microcircuit devices as a whole.

Both the vendor and nonvendor data in Figure 1 show a decreasing linear failure rate with the reciprocal of the absolute temperature, thus verifying the use of the Arrhenius model for applications in aging processes in which temperature is the only accelerating factor. In addition, the trend lines for the vendor and nonvendor data are not significantly different. Because of their mathematical similarity, the vendor and nonvendor data may be logically combined, the resulting Arrhenius curve determined, and

TABLE XIII

Observed Catastrophic Storage Failures Rates Microcircuits
(Primarily Military Standard Class) for Normal
Temperatures

| | Vendor Data | | | Nonvendor Data | | |
|---|---|---|---|---|---|---|
| | Experience (25° C) Part Hours ($X10^6$) | Failures | λ Fits | Experience (25°C) Part Hours ($X10^6$) | Failures | λ Fits |
| Integrated circuits | | | | | | |
| DTL | 118.7458 | 5 | 42.1 | 0.5930 | 0 | < 1686 |
| RTL | 38.5640 | 2 | 51.9 | 1,166.6402 | 20 | 17.1 |
| RCTL | 0.1400 | 0 | < 7143 | 0.2140 | 0 | < 4673 |
| Not identified | 27.200 | 1 | 36.8 | 7.5750 | 0 | < 132 |
| Sub totals | 184.6498 | 8 | 43.3 | 1,175.0222 | 20 | 17.0 |
| Total vendor and Nonvendor | | | | 1,359.6720 | 28 | |

TABLE XIV

Observed Catastrophic Dormant Failure Rates Microcircuits (Primarily Military Standard Class) for Normal Temperatures

| | Vendor Data | | | Nonvendor Data | | |
|---|---|---|---|---|---|---|
| | Experience (25°C) Part Hours ($X10^6$) | Failures | λ Fits | Experience (25°C) Part Hours ($X10^6$) | Failures | λ Fits |
| Integrated circuits | | | | | | |
| DTL | 8.5154 | 0 | < 118 | 1234.2786 | 49 | 39.7 |
| RTL | 6.0625 | 0 | < 165 | 8.6570 | 1 | 115 |
| RCTL | -- | - | -- | 5.6430 | 1 | 177 |
| MECL | 16.1780 | 0 | < 61.8 | -- | - | -- |
| DCTL | 5.1697 | 0 | < 193 | -- | - | -- |
| $T^2L$ | 3.6080 | 0 | < 277 | -- | - | -- |
| Linear | -- | - | -- | 113.4833 | 6 | 52.9 |
| Not identified | -- | - | -- | 21.1960 | 6 | 283 |
| Totals | 39.5336 | 0 | < 25.3 | 1383.2579 | 63 | 45.5 |
| Total vendor and nonvendor | | | | 1422.7915 | 63 | 44.3 |

TABLE XV

Military Standard Microcircuit
Storage Failure Data by Source Type

| Nonvendor Data Field and Laboratory | | | | Vendor Data Field and Laboratory | | |
|---|---|---|---|---|---|---|
| Experience Part Hours ($X10^6$) | Number of Catastrophic Failures | Catastrophic Failure Rate ($\lambda$ Fits) | Temperature (°C) | Experience Part Hours ($X10^6$) | Number of Catastrophic Failures | Catastrophic Failure Rate ($\lambda$ Fits) |
| 1175.022 | 20 | 17.0 | 25 | 184.650 | 8 | 43.3 |
| 8.964 | 9 | 1000 | 125 | 6.326 | 9 | 1420 |
| 2.534 | 6 | 2370 | 150 | 21.621 | 34 | 1570 |
| 0.619 | 1 | 1615 | 175 | 6.213 | 23 | 3700 |
| 1.028 | 15 | 14600 | 200 | 6.847 | 32 | 4670 |
| -- | -- | -- | 250 | 1.213 | 17 | 14000 |
| 0.366 | 9 | 24600 | 300 | 1.835 | 43 | 23400 |

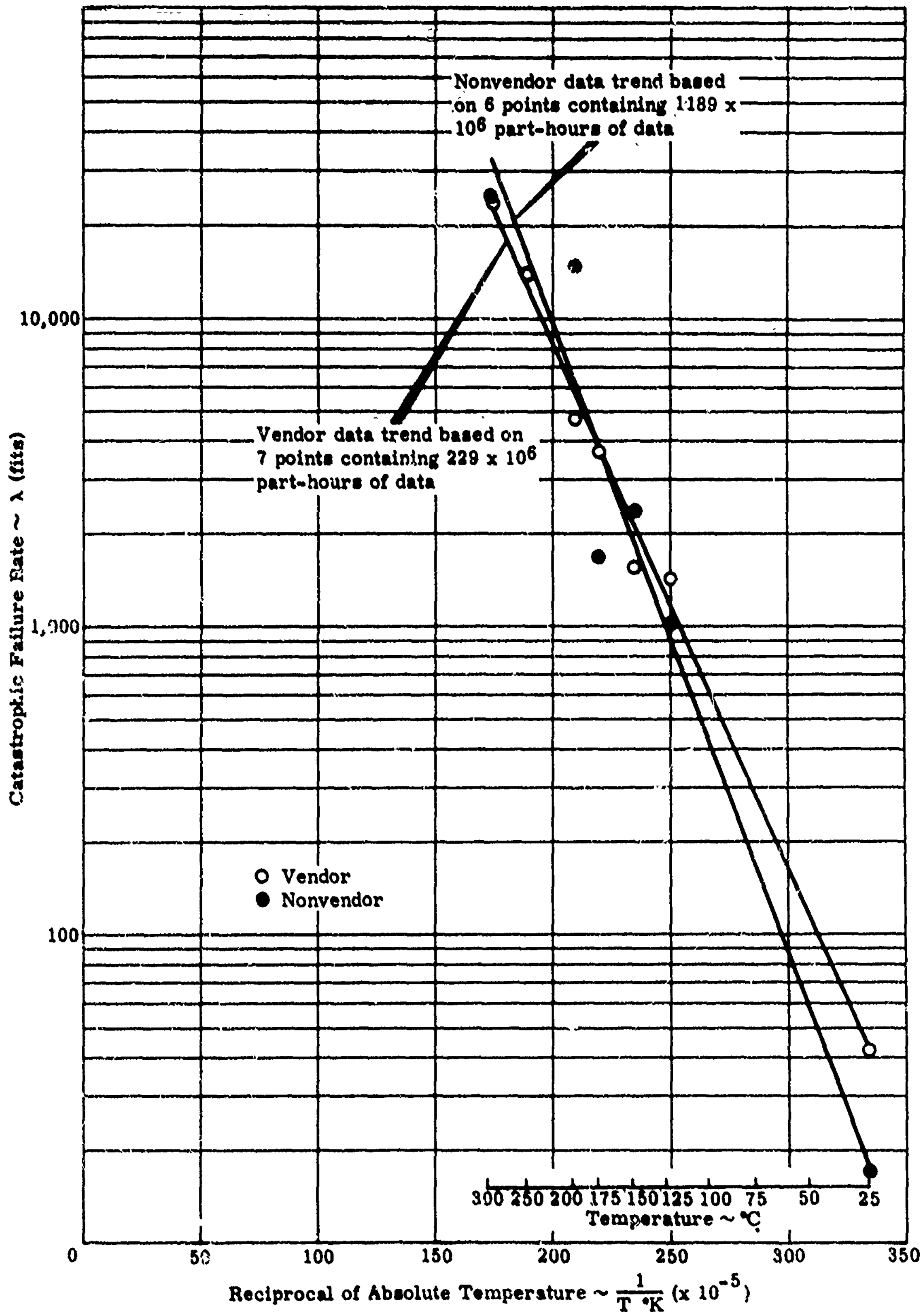



Figure 1. Arrhenius Plots of Military Standard Microcircuit Catastrophic Failure Rates
Vendor versus Nonvendor Data

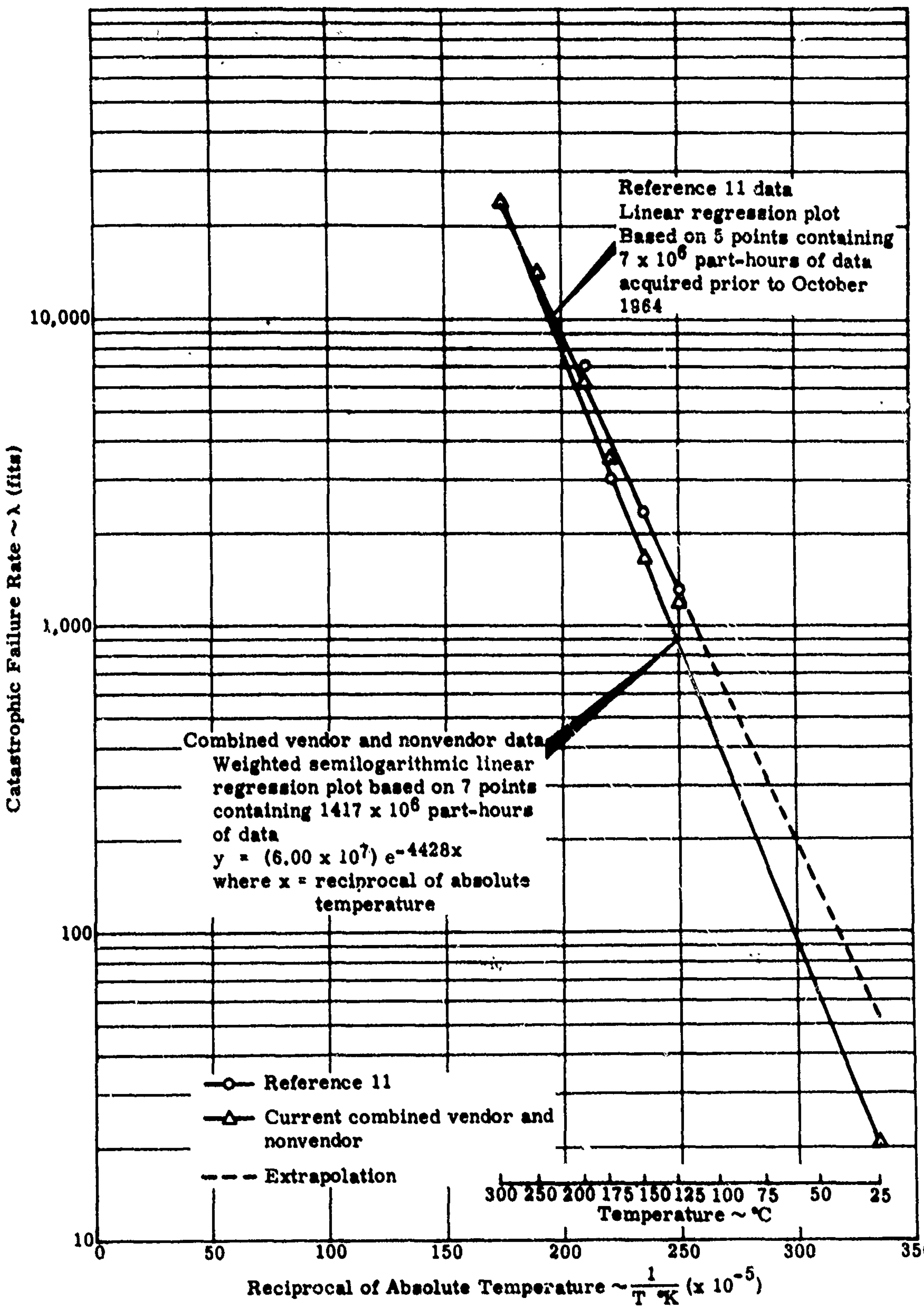



Figure 2. Arrhenius Plots of Catastrophic Microcircuit Storage Failure Rates, Combined Vendor and Nonvendor Data

this resulting curve used as the basis to determine failure rates and acceleration factors. Table XVI presents the combined data.

TABLE XVI

Military Standard Microcircuit Storage Failure Data
Sources Combined

| Temperature (°C) | Reciprocal of Absolute Temperature (1/°K) | Experience Part-Hours ($X10^6$) | Number of Catastrophic Failures | Observed Catastrophic Failure Rates Fits |
|---|---|---|---|---|
| 25 | 0.00336 | 1,359.672 | 28 | 20.6 |
| 125 | 0.00251 | 15.290 | 18 | 1,180 |
| 150 | 0.00236 | 24.155 | 40 | 1,660 |
| 175 | 0.00223 | 6.832 | 24 | 3,510 |
| 200 | 0.00211 | 7.875 | 47 | 5,970 |
| 250 | 0.00191 | 1.213 | 17 | 14,000 |
| 300 | 0.00175 | 2.201 | 52 | 23,600 |

The combined data from Table XVI are plotted in Figure 2; a weighted semilogarithmic linear regression analysis has been performed, and the resulting straight line plotted. The weighted analysis accounts for the quantity of data for each point and proportionately emphasizes each point by the preponderance of its data with respect to the total quantity of data. The regression analysis is shown in Appendix D.

In addition, Figure 2 shows a comparison of the present Arrhenius plot of the combined military standard microcircuit catastrophic storage failure data to an Arrhenius plot in Reference 11. The agreement between both of these Arrhenius plots can be readily seen, especially in the 175 to 250 range for the reciprocal of absolute temperature. The minor difference between these two curves can be attributed to 1) the Arrhenius plot from Reference 11 is based on a small quantity of data over a limited range of reciprocal temperatures. This means the slope of the curve is sensitive to the individual data points. As little as a 3 degree change in the slope of the Reference 11 curve would make it colinear with the current data curve; 2) the Arrhenius plot from Reference 11 is based on microcircuit data prior to October 1964, while the combined vendor and nonvendor plot contains data as recent as January 1967. Reliability growth, where demonstrated in more recently manufactured microcircuits, would result in the reduction of the failure rates associated with them. These lower failure rates afford good reason for affecting the slope of the combined vendor and nonvendor data Arrhenius plot. They also serve to both rotate

and translate the curve from the Reference 11 prediction (with extrapolation) to the current well-validated location shown in Figure 2.

The best indication of the average catastrophic failure rates for field or laboratory storage as a function of temperature is shown in Figure 3. This Figure is based on the assumption of an exponential relationship of the catastrophic failure rate and the reciprocal of absolute temperature as shown in Figure 2.

The catastrophic failure rate of 20.6 fits for storage at 25°C is significant if only for the reason that the amount of experience on which it is based, about 1.36 billion part-hours, is the largest quantity of storage data obtained to date for microcircuits.

2) Analysis of Dormant Operating Data

The determination of the catastrophic failure rate of high reliability microcircuits versus temperature may properly begin with a review of all the vendor and nonvendor dormant operating data in order to derive meaningful information and evaluate any apparent implications or anomalies. Table XVII shows the difference between vendor and nonvendor data and that there is currently not a sufficient number of data points to permit the construction of an Arrhenius curve based on a semilogarithmic linear regression analysis.

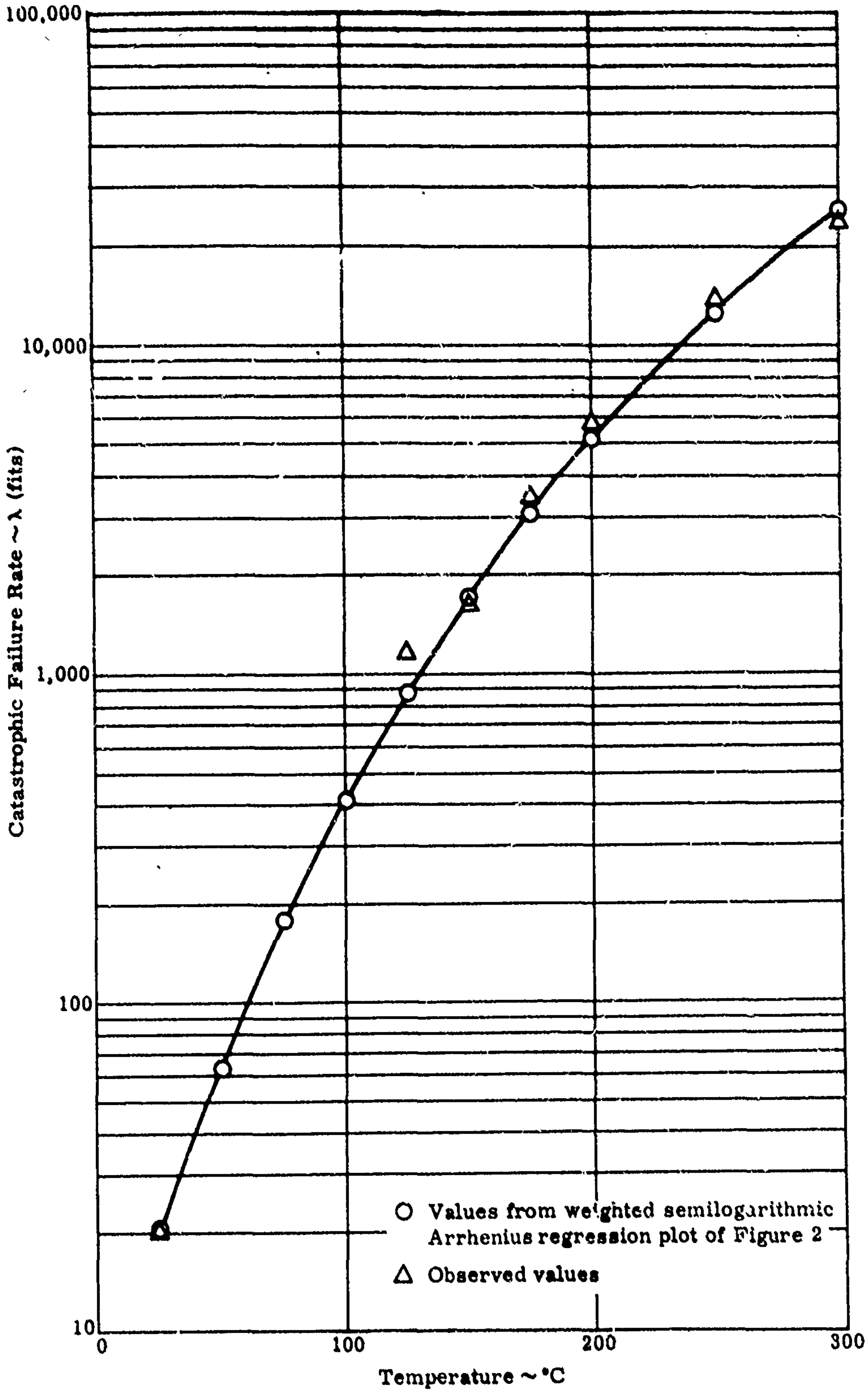



Figure 3. Average Catastrophic Storage Failure Rates for All Types of Military Standard Microcircuits in Various Conditions of Field or Laboratory Storage (Combined Vendor and Nonvendor Data)

TABLE XVII

High Reliability Microcircuit Dormant Operating Failure Data
by Source Type

| | Nonvendor Data (Field and Laboratory) | | | Vendor Data (Laboratory Only) | | | Combined Vendor and Nonvendor Data Field and Laboratory | | |
|---|---|---|---|---|---|---|---|---|---|
| Temp (°C) | Experience Part Hours ($X10^6$) | Number of Catastrophic Failures | Catastrophic Failure Rate ($\lambda$ Fits) | Experience Part Hours ($X10^6$) | Number of Catastrophic Failures | Catastrophic Failure Rate ($\lambda$ Fits) | Experience Part Hours ($X10^6$) | Number of Catastrophic Failures | Catastrophic Failure Rate ($\lambda$ Fits) |
| 25 | 1383.211 | 63 | 45.5 | 39.581 | 0 | < 25.3 | 1422.792 | 63 | 44.3 |
| 125 | 31.335 | 22 | 702 | 120.059 | 21 | 175 | 151.394 | 43 | 284 |
| 150 | 0.147 | 0 | < 6800* | -- | -- | -- | 0.147 | 0* | < 6800* |

*Assumes 1 failure

## B. ENVIRONMENTAL FACTORS

### 1. Temperature Factors

The data accumulated are from varying temperature conditions. Some equipment underwent cyclic temperature stress, while other equipment remained at almost constant temperature.

#### a. Military Standard Parts

Approximately one percent of the military standard parts data were obtained from equipment stored under natural climatic cyclic stresses which ranged from -65 to +160°F, 95 percent from +10° to +110°F, and 4 percent at a constant temperature. When combined, all data experienced an average climatic temperature of +73°F. Because of the limited temperature range and inability to determine exact mean storage temperature, no pronounced difference in the equipment storage catastrophic failure rates can be identified between the group of equipment stored at a constant temperature and either group of equipment that underwent temperature cycles.

#### b. High Reliability Parts

Approximately 30 percent of the high reliability parts data were obtained from equipment subjected to natural climatic cyclic stresses in transportation and depots. The most probable temperature range associated with this data is +10 to +110°F, with an average of 75 ±5°F. Seventy percent of the data was obtained from equipment in environmentally controlled chambers held at a constant temperature of 77°F. When combined, all data experienced an average temperature of 77°F. No pronounced difference in the catastrophic failure rates, storage or dormant operating, can be identified between the group of equipment at a constant temperature and the group of equipment that underwent temperature cycles.

### 2. Humidity Factors

#### a. Military Standard Parts

The data accumulated on military standard parts were observed to be within a humidity range of 5 to 100 percent and to have a mean of 67 percent. Approximately 60 percent of the data was from equipment stored at a relatively constant humidity while 40 percent was from equipment subjected to humidity cycling.

The data were sorted into predominant humidity percentiles and the failure rate for each determined. This analysis approach failed to yield a significant difference between the various percentiles. The reason has been attributed to one or more of the following factors.

1 The method of data grouping cannot account for humidity cycling effects;

2 The degree of humidity protection afforded each group of equipments varied within each percentile and from percentile to percentile;

3 Data having a humidity equal to or near a percentile transition point might unduly bias the percentile into which it has been grouped.

Since the analysis approach by humidity percentiles yielded no usable results on humidity effects on failure rates, another approach was tried to evaluate the effects of humidity on equipment not in a container versus equipment in a container with humidity control. The results of this approach are described in paragraph 3 of this section.

b. High Reliability Parts

Since approximately 100 percent of the data on high reliability parts was maintained at a relatively constant humidity, no analysis could be made concerning the effects of various humidities.

3. Location, Transportation, and Handling Factors

a. Military Standard Parts

Packaging, handling, shipping, and other combined environmental effects at different locations indicated a significant difference in the nonoperating failure rates. Data from the various laboratory locations where the parts were stored, handled, and exposed to typical laboratory conditions have been accumulated to give a factor for the laboratory mode. Data from the depots and/or warehouses where the parts were shipped, handled, packaged, stored, and exposed to different environmental conditions either in or out of containers affording environmental protection have been accumulated to give a factor for the depot and/or warehouse mode. Data from parts shipped and stored under field conditions have been accumulated in a similar manner to give a factor for the field mode. The nonoperating location mode factors ($K_L$) that include effects of transportation and handling have been calculated by using the accumulated

failure rates on all electronic parts in each mode and determining appropriate ratios, equating the laboratory environment to unity. These factors are given below in Table XVIII. Before additional breakdowns of location mode factors can be accomplished, accumulation of more data is necessary. It should also be noted that these $K_L$ factors are not intended as multipliers for the nonoperating discrete part failure rates shown in this report, but rather are intended as severity indicators.

TABLE XVIII

Nonoperating Location Mode Factors ($K_L$) for Various Modes for Military Standard Part Class (Normalized to Laboratory Nonoperating)

| Nonoperating Environment | Location Mode Factor ($K_L$) | Part-Hours of Experience ($X10^6$) |
|---|---|---|
| Laboratory | 1.0 | 23,110 |
| Depot and/or warehouse in container | 1.3 | 2,093 |
| Depot and/or warehouse not in container | 4.0 | 46,912 |
| Field in container | 4.4 | 203 |
| Field not in container | 21.3 | 1,441 |

b. High Reliability Parts

Almost 100 percent of the data in the high reliability part category has been collected from equipment in like field modes. As a result, no location mode factors can be developed from current data for established reliability parts.

c. Microcircuits

Over 96 percent of the microcircuit data has been collected from equipment in the field from nonvendor sources. About 3 percent has been collected from vendor laboratory sources.

Estimates of the location mode factors ($K_L$) can be developed for storage and dormant operation. Table XIX presents these factors. It should also be noted that Table XIX factors are not intended as multipliers for the nonoperating failure rates shown in this report, but rather are intended as severity indicators.

TABLE XIX

Storage and Dormant Operating Location Mode Factors ($K_L$) for Various Modes for Microcircuit Part Class (Normalized to Laboratory Storage)

| Nonoperating Environment | Location Mode Factor ($K_L$) Storage | Dormant Operating | Experience Part-Hours ($X10^6$) |
|---|---|---|---|
| Laboratory | 1.0 | 1.9 | 113.9 |
| Depot, warehouse, or chamber having environmental control | 1.3 | 3.3 | 2549.9 |

C. CONSTRUCTION OF CATASTROPHIC FAILURE RATE TABLES

1. Military Standard Parts, Nonoperating Storage

A preliminary failure rate table (Reference 70) was constructed before this program began. This was based on over 2 billion part-hours of experience and the engineering judgement of part specialists who applied ranking analysis techniques to the various categories of parts under their cognizance.

The addition of over 74 billion part-hours experience compiled on military standard parts in this program has not, in itself, obviated the need for engineering judgment. Rather, such a number has demanded more careful engineering judgment because of its magnitude and the effects of its application.

Therefore, parts descriptions have been studied and raw data censored so it could be applied to the best advantage in constructing Table XX. In so doing, some of the data had to be discarded. For example: filters, listed under Inductive Devices, in the raw data had to be set aside because it is more likely that the filters were actually capacitors. Fortunately, such examples were the exception.

More often, apparent anomalies arose where the raw data did not seem to bear out the earlier rank ordering that had been developed. For instance, the reliability of transistors was ranked in the order of the type of construction and processing; planar first, mesa next, and alloy last. Other authorities have concurred with this judgment and some have

TAB

Catastrophic Failure Rates Nonope

| Catastrophic Nonoperating Failure Rate in Fits (Failures/$10^9$ Part-Hours) | 1 Resistors and Frequency Determining Devices | 2 Capacitors | 3 Semiconductors and Microcircuits ~All Devices Si Except (Ge)~ | 4 Transformers and Inductors | Electro Rotatin |
|---|---|---|---|---|---|
| 10,000 | | | | | |
| 5,000 | | | | | Synchro devic |
| 2,000 | | | | | Electromechanic; AC and DC meter |
| 1,000 | | | Hybrid microcircuits, discrete | | DC tor |
| 500 | | | Hybrid microcircuits, thin film | Variable autotransformer | AC motor; Gyros |
| 200 | | Aluminum, electrolytic | Silicon controlled rectifier; Unijunction transistor; Medium power diode, micro | Variable RF coils open; RF transformer | AC se |
| 100 | Piezoelectric quartz crystal | | Hybrid circuit, thick film; Monolithic microcircuit, analog | Variable RF coils molded; Power coils | Acceler |
| 70 | | | Monolithic microcircuit, digital; Micromodules; High power alloy transistor (Ge) | | |
| 50 | | | Microwave diodes; High power alloy transistor; High power mesa transistor | RF chokes, coils | DC, power, mot |
| 30 | | | | | |
| 20 | | Variable ceramic (CV); Variable ceramic, tubular; Variable glass, tubular; Tantalum, wet, foil and slug | High power diode, zener; Low power diode, micro; Field effect transistor junction; High power planar transistor; Low power alloy transistor switch (Ge) | Magnetic amplifier | AC, power,; AC, power,; AC, generat |
| 15 | | | Medium power alloy transistor | | |
| 10 | | Variable air; Mica | Medium power diode, zener; Low power diode, (Ge); Medium power mesa transistor; Low power alloy transistor | Pulse transformer; Power transformer | |
| 7 | | | Low power mesa transistor; Medium power planar transistor | | |
| 5 | Variable carbon composition; Variable wirewound; Variable trimmer, wirewound; Variable trimmer, metal film; Carbon film; Wirewound, precision; Thermistors and varistors | | Low power diode, zener; Bridges, 4 diodes encapsulated; High power diode | Power reactors, inductors, and chokes | |
| 3 | | Metallized Mylar; Metallized polycarbonate; Metallized paper; Tantalum, solid; Foil, paper; Foil, paper-Mylar | Low power planar transistor; Medium power diode | | |
| 2 | Wirewound, power | | | Audio transformer | |
| 1.5 | | | | | |
| 1 | Metal film; Tin oxide | Foil, Mylar; Foil polycarbonate; Foil, polystyrene; Ceramic, general purpose | Low power diode | | |
| 0.5 | | | | | |
| 0.2 | | Foil, Teflon; Ceramic temperature compensating; Porcelain; Glass | | | |
| 0.1 | Carbon composition | | | | |
| 0.05 | | | | | |
| 0.02 | | | | | |
| 0.01 | | | | | |
| 0.005 | | | | | |

*Fits per pin socket connector

A

B

TABLE XX

Catastrophic Failure Rates Nonoperating Storage Mode, Military Standard Parts

| ...mers<br>...ctors | 5<br>Electromechanical<br>Rotating Devices | 6<br>Switches and Relays | 7<br>Connectors* and<br>Electron Tubes | 8<br>Hydraulics | 9<br>Pyrotechnical and<br>Electrochemical<br>Devices | Mic...<br>H... |
|---|---|---|---|---|---|---|
| | | | | Electrohydraulic servos | | |
| | Synchro devices, brush type | | | Pumps/motors<br>Seals, dynamic | Ag - Zn primary batteries<br>Explosive bolts | |
| | Electromechanical timers<br>AC and DC meters, panel, D'Arsonval | Acceleration timer switch<br>Interval timer | | | | |
| | DC torquers | Thermal timer<br>Stepper, Ledex, industrial type<br>Stepper, telephone type<br>Electronic timers | | Electrohydraulic transducers | | C... |
| ...nsformer | AC motor tachometers<br>Gyros | Thermal switch<br>Dry circuit relay<br>Sensitive relay, opening < 100 MW<br>Motor driven timer<br>Pressure switch | | | Detonators<br>Igniters | |
| ...ils, open | AC servos | Circuit breaker<br>Contractor, load > 10 Amp<br>Push button switch<br>Precision switch, limit<br>Inertial switch<br>Sequential timer | | | Actuators | |
| ...ils, molded | Accelerometer | Armature relay<br>Rotary switch<br>Toggle switch | | Fluids, lubricants<br>Solenoid operated valves<br>Servo valve | Bellows<br>Timers | |
| ...coils | DC, power, motors and generators | One-sixth size crystal can relay<br>Half size crystal can relay | | | | |
| ...plifier | AC, power, induction motor<br>AC, power, synchronous motor<br>AC, generators | Reed relay | Electron tubes, receiver type | | Squibs<br>Motors | |
| ...former<br>...former | | Crystal can relay | | Accumulators<br>Actuators hydraulic<br>Static seals<br>Self-operating valves<br>Regulators | Switch | |
| ...tors, and chokes | | | Tape | | | Insul...<br>Bear... |
| | | | | | | |
| ...former | | Mercury wetted relay | Coaxial, all types<br>Signal, rectangular, crimp, high density<br>Signal, rectangular, solder, miniature<br>Signal, edge, crimp<br>Signal, rectangular, crimp, miniature<br>Signal, pin socket, solder<br>Signal, pin socket, crimp<br>Signal, edge, solder<br>Power, rectangular, solder, blind mate<br>Power, rectangular, crimp, blind mate<br>Power, rectangular, solder, screw lock<br>Power, rectangular, crimp, screw lock | Relief valves<br>Check valves | | |
| | | | | | | |
| | | | Signal, rectangular, solder, high density<br>Signal, circular, solder, high density<br>Power, bayonnet, solder<br>Power, threaded, solder<br>Power, bayonet, crimp<br>Power, threaded, crimp | | | |
| | | | Signal, circular, solder, miniature<br>Signal, circular, crimp, high density<br>Signal, circular, crimp, miniature | Gauges | | |
| | | | | | | |
| | | | | Reservoirs<br>Manual valves | | Gen...<br>Stra... |
| | | | | Fittings, tubing-flexible | | Clut...<br>Slin...<br>Cont... |
| | | | | | | Quick<br>Quick<br>Clam... |
| | | | | | | Inserts<br>Nuts<br>Bolts and<br>Bolts and<br>Permane... |
| | | | | | | I...<br>S... |

B

C

| 8 Hydraulics | 9 Pyrotechnical and Electrochemical Devices | 10 Microwave and Hardware | |
|---|---|---|---|
| Electrohydraulic servos | | | 10,000 |
| Pumps/motors<br>Seals, dynamic | Ag -/Zn primary<br>batteries<br>Explosive bolts | | 5,000 |
| | | | 2,000 |
| Electrohydraulic transducers | | Cavities | 1,000 |
| | Detonators<br>Igniters | | 500 |
| | Actuators | | 200 |
| Fluids, lubricants<br>Solenoid operated valves<br>Servo valve | Bellows<br>Timers | | 100 |
| | | | 50 |
| | Squibs<br>Motors | | 20 |
| Accumulators<br>Actuators hydraulic<br>Static seals<br>Self-operating valves<br>Regulators | Switch | | 10 |
| | | Insulators, rubber<br>Bearings | 5 |
| | | | |
| Relief valves<br>Check valves | | | 2 |
| | | | |
| | | | 1 |
| Gauges | | | 0.5 |
| | | | 0.2 |
| Reservoirs<br>Manual valves | | Gears<br>Strap assemblies | 0.1 |
| Fittings tubing-flexible | | Clutches<br>Slings<br>Containers, sealed | 0.05 |
| | | Quick release pins<br>Quick release fasteners<br>Clamps and couplings | 0.02 |
| | | Inserts<br>Nuts<br>Bolts and screws, structural<br>Bolts and screws, nonstructural<br>Permanent fasteners | 0.01 |
| | | Blind rivets<br>Solid rivets | 0.005 |

predicted that the planar process will be the one that survives (Reference 44). Yet, the raw data indicate that high power alloy transistors are more reliable than high power mesa transistors. The low power transistor data seem to validate the original judgment, as far as may be required for a 50 percent decade scale (Reference 47). This enabled taking a first step in ranking failure rates for a possible military standard parts catastrophic failure rate table as initially seen in Table XXV and Table XXVI of Reference 58.

a. Influence of High Reliability Experience Data on Military Standard Parts Storage Failure Rates

The addition of about 190 billion part-hours of high reliability storage experience has enabled a second step to be taken in ranking of military standard failure rates along with taking a first step in ranking high reliability storage failure rates (Table XXI).

Table XXI has been constructed using the weight of the very substantial experience data accumulated for low power planar transistors and low power diodes as a foundation for the low failure rate end of the scale. The higher end of the scale has been influenced by the considerable amount of experience data for low and high power alloy germanium transistors.

Engineering judgment in the use of ranking analysis has been used wherever experience data are insufficient or lacking by recognizing considerations such as:

1 The higher reliability inherent in silicon compared with germanium for higher temperature military applications,

2 A transistor is essentially two diodes back to back,

3 The consistently higher failure rate seen for zener diodes in the raw data was accepted and explained by the fact that less standardized design can be seen in the construction of zener diodes. In addition, two pellets are sometimes used in zener diodes, especially in reference units to secure low temperature coefficients.

The failure rates obtained for military standard parts in the second step are generally lower than estimated in the first step. The large amounts of experience data obtained from both military standard and high reliability sources has also made it possible to use a 25 percent decade scale with finer resolution and the added advantage of providing closer correlation with key raw data failure rate values.

TABLE XXI

Catastrophic Failures per $10^9$ Part-Hours, Fits, Parts in Storage

| Semiconductor Devices all Si except (Ge) | Original Estimated Ranking, Failure Rates | Military Standard Parts | | | | | High Reliability Parts | | | | Original Estimated Ranking, Failure Rates |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Experience Part-Hours $\times 10^6$ | No. of Failures | Raw Data Failure Rates | 1st Step Ranking Failure Rates | 2nd Step Ranking Failure Rates | 1st Step Ranking Failure Rates | Raw Data Failure Rates | No. of Failures | Experience Part-Hours $\times 10^6$ | |
| SCR, silicon controlled rectifier | - | 4.84 | 0 | <207 | 200 | 200 | 50 | - | - | No data | - |
| High power alloy transistor (Ge) | - | 5.58 | 0 | <179 | - | 70 | 7 | 6.6 | 5 | 756.3 | - |
| High power alloy transistor | 1,000 | 61.8 | 1 | 16.2 | 200 | 50 | 5 | - | - | No data | 200 |
| High power mesa transistor | 500 | 26.3 | 4 | 152 | 100 | 50 | 5 | - | - | No data | 100 |
| High power planar transistor | 50 | No data | - | - | 50 | 30 | 3 | <776 | 0 | 1.29 | 20 |
| Low power alloy transistor, switch (Ge) | - | 1,118.0 | 30 | 26.8 | 50 | 30 | 3 | 2.81 | 23 | 8,184.6 | - |
| Low power alloy transistor | - | 133.5 | 10 | 74.9 | 20 | 15 | 1.5 | - | - | No data | - |
| Low power mesa transistor | 20 | 36.0 | 1 | 27.7 | 10 | 10 | 1 | - | - | No data | 10 |
| Medium power planar transistor | 20 | 311.8 | 0 | <3.2 | 10 | 10 | 1 | <761 | 0 | 1.32 | 10 |
| Low power diode, zener | - | 1,279.0 | 3 | 2.3 | 2 | 7 | 1 | 3.36 | 7 | 2,085.1 | 2 |
| Low power planar transistor | 10 | 166.2 | 4 | 24.1 | 5 | 3 | 0.7 | 0.58 | 12 | 20,581.7 | 1 |
| Low power diode | 5 | 11,706.7 | 8 | 0.7 | 2 | 1 | 0.3 | 0.29 | 14 | 48,190.4 | 1 |

A 3 to 1 ratio for military standard part failure rates to those of high reliability is now observed at the lower end of the failure rate scale. This ratio rises to about 10 to 1 at the higher end of the failure rate scale.

b. Problem Areas and Accuracy

A continuous source of anomalies from raw data concerns low population items where the amount of experience data available is insufficient. Where no failures have been observed, the technique of assuming one failure to calculate a "less than" failure rate value produces some discontinuities which also require engineering judgment to rationalize and smooth the scale of failure rates.

This philosophy has been used throughout the construction of Table XX for military standard parts and Table XXII for high reliability parts. Engineering judgment will continue to be required until equally large amounts of experience data and numbers of failures become available for all the different kinds and reliability grades of parts. Meanwhile, it is believed that use of the failure rates shown in the failure rate tables will result in conservative predictions and safe design practices, especially for the large population items in column 1, 2, and 3 of both Tables since the items contained therein represent the majority of the experience data accumulated.

Tables XX and XXII do not faithfully reflect raw data failure rates. The disparity of experience data in many areas would not permit this. No special claims are made for demonstrated accuracy because of the amount of necessary engineering judgment involved.

c. Validation

Over 76 billion part-hours of experience data were considered for all categories of Table XX, Military Standard. The only items with some validation in column 8, Hydraulics, and column 10, Microwave Hardware are:

1 Servovalves: $29 \times 10^6$ part-hours, 2 failures; 68.9 fits,

2 Microwave cavities: $1 \times 10^6$ part-hours, 0 failures; < 945 fits.

2. High Reliability Parts, Nonoperating Storage

a. Validation

The large population parts failure rates found in column 1, 2, and 3 of Table XXII are now validated on the basis of about 190 billion part-

TABLE XXII

Catastrophic Failure Rates Nonoperating Storage Mode, High Reliability Pa

| Catastrophic Nonoperating Failure Rate in Fits (Failures/$10^9$ Part-Hours) | 1 Resistors and Frequency Determinating Devices | 2 Capacitors | 3 Semiconductors and Microcircuits ~All Devices Si Except (Ge)~ | 4 Transformers and Inductors | Ele Ro |
|---|---|---|---|---|---|
| 10,000 | | | | | |
| 5,000 | | | | | |
| 2,000 | | | | | Synchro devi |
| 1,000 | | | | | Electromecl<br>AC and DC |
| 500 | | | Hybrid microcircuits, discrete | Variable autotransformers | DC torquers |
| 200 | | | Hybrid microcircuits, thin film | Variable RF coils, open | AC motor t |
| 100 | Piezoelectric quartz crystal | | | Variable RF coils, molded | AC servos |
| 50 | | Aluminum, electrolytic | SCR, silicon controlled rectifier<br>Unijunction transistor | | DC motors,<br>DC generat |
| 30 | | | Medium power diode, micro | | |
| 20 | | | Monolithic microcircuit, analog<br>Thick film hybrid circuit | | |
| 10 | | | Micromodules<br>Monolithic microcircuit, digital | RF chokes, coils | AC motors,<br>AC motors<br>AC generat |
| 7 | | | High power alloy transistor (Ge)<br>Microwave diodes | | |
| 5 | Variable, carbon composition<br>Variable, wirewound<br>Variable trimmer, wirewound<br>Variable trimmer, metal film | Variable ceramic (CV)<br>Variable ceramic, tubular<br>Variable glass, tubular | High power alloy transistor<br>High power mesa transistor<br>High power diode, zener<br>Low power diode, micro | | |
| 3 | Carbon film<br>Thermistors and varistors | | Field effect transistor, junction<br>High power planar transistor<br>Low power alloy transistor, switch (Ge) | | |
| 2 | | Tantalum, wet: foil and slug<br>Variable air | Medium power alloy transistor<br>Medium power diodes, zener<br>Low power diode (Ge) | Nonhermetic filament transformer<br>Nonhermetic pulse transformer PkV > 1000<br>Nonhermetic mag. amplifier<br>Nonhermetic audio transformer<br>Nonhermetic pulse transformer, PkV < 1000<br>Nonhermetic power transformer<br>Nonhermetic power reactor | |
| 1.5 | | | Medium power mesa transistor<br>Low power alloy transistor | | |
| 1 | Wirewound, precision | Mica | Low power mesa transistor<br>Medium power planar transistor<br>Low power diodes, zener<br>Bridges, 4 diodes encapsulated | Hermetic mag. amplifier<br>Hermetic audio transformer<br>Hermetic pulse transformer PkV > 1000<br>Hermetic power transformer | |
| 0.7 | | | High power diode<br>Low power planar transistor | | |
| 0.5 | | Metallized Mylar<br>Metallized polycarbonate<br>Metallized paper<br>Foil, paper<br>Foil, paper Mylar | Medium power diode | Hermetic pulse transformer, PkV < 1000<br>Hermetic power reactor | |
| 0.3 | | | Low power diode | | |
| 0.2 | Wirewound, power<br>Tin oxide<br>Metal film | Tantalum, solid<br>Foil, Mylar<br>Foil, polycarbonate<br>Foil, polystyrene<br>Ceramic, general purpose | | | |
| 0.1 | | | | | |
| 0.05 | Carbon composition | Foil, Teflon<br>Porcelain<br>Glass<br>Ceramic, temperature compensating | | | |
| 0.02 | | | | | |
| 0.01 | | | | | |

*Powder charge and bridgewire.
†Fits per pin socket connection

A

B

TABLE XXII

ilure Rates Nonoperating Storage Mode, High Reliability Parts

| 4<br>Transformers and Inductors | 5<br>Electromechanical Rotating Devices | 6<br>Switches and Relays | 7<br>Connectors† | |
|---|---|---|---|---|
| | | | | 10,000 |
| | | | | 5,000 |
| | Synchro devices, brush type | Acceleration timer switch | | 2,000 |
| | Electromechanical timers<br>AC and DC meters, panel, D'Arsonval | Thermal timer | | 1,000 |
| Variable autotransformers | DC torquers | Thermal switch<br>Stepper, ledex, industrial type<br>Stepper, telephone type<br>Electronic timers | | 500 |
| Variable RF coils, open | AC motor tachometers | Dry circuit relay<br>Sensor relay, opening < 100 MW | | 200 |
| Variable RF coils, molded | AC servos | Circuit breaker<br>Contactor, load > 10 Amp<br>Push button switch<br>Precision switch, limit<br>Squib* | | 100 |
| | DC motors, power<br>DC generators | Rotary switch<br>Toggle switch | | 50 |
| | | One-sixth size crystal can relay<br>Half size crystal can relay | | 20 |
| RF chokes, coils | AC motors, induction, power type<br>AC motors synchronous power type<br>AC generators | Reed relay | | 10 |
| | | Microminiature crystal can relay<br>Squib switch | Tape | 5 |
| Nonhermetic filament transformer<br>Nonhermetic pulse transformer PkV > 1000<br>Nonhermetic mag. amplifier<br>Nonhermetic audio transformer<br>Nonhermetic pulse transformer, PkV < 1000<br>Nonhermetic power transformer<br>Nonhermetic power reactor | | | Coaxial, all types<br>Signal, rectangular, crimp, high density<br>Signal, rectangular, solder, miniature<br>Signal, edge, crimp<br>Signal, rectangular, crimp, miniature<br>Signal, pin socket, solder<br>Signal, pin socket, crimp<br>Signal, edge, solder<br>Power, rectangular, solder blind mate<br>Power, rectangular, crimp, blind mate<br>Power, rectangular, solder, screw lock<br>Power, rectangular, crimp, screw lock | 2 |
| Hermetic mag. amplifier<br>Hermetic audio transformer<br>Hermetic pulse transformer PkV > 1000<br>Hermetic power transformer | | Mercury wetted relay | Signal, rectangular, solder, high density<br>Signal, circular, solder, high density<br>Power, bayonet, solder<br>Power, threaded, solder<br>Power, bayonet, crimp<br>Power, threaded, crimp | 1 |
| Hermetic pulse transformer, PkV < 1000<br>Hermetic power reactor | | | Signal, circular, solder miniature<br>Signal, circular, crimp, high density<br>Signal, circular, crimp, miniature | 0.5 |
| | | | | 0.2 |
| | | | | 0.1 |
| | | | | 0.05 |
| | | | | 0.02 |
| | | | | 0.01 |

B

hours experience data ranked in the manner shown in Table XXI.

b. Failure Rates

The average failure rate for all the electronic discrete parts in the high reliability group is 74 failures ÷ 189.9 x $10^9$ part-hours = 0.390 fits, in storage. The average failure rate for all the electronic military standard parts is 216 failures ÷ 71.8 X $10^9$ part-hours = 3.01 fits, in storage.

A ratio of about 7.7 times (3.01 ÷ 0.390 = 7.7) higher failure rates is thus found for electronic military standard parts in storage, on the average, compared with electronic high reliability parts all contained in column 1, 2, and 3.

The failure rates given in columns 4 through 7 of Table XXII are either shown the same as first estimated in Table XX or improved based on various reports current in the industry. They represent best engineering judgment at this time.

3. Dormant Operating Mode, High Reliability

The average failure rate for all discrete electronic high reliability parts in the dormant mode is 554 failures ÷ 441.6 x $10^9$ part-hours = 1.25 fits. Thus, a dormant to storage ratio factor for high reliability parts can be determined as 1.25 fits, dormant ÷ 0.390 fits, storage = 3.21 times, and Table XXII may also be used for the dormant nonoperating mode when the 3.21 times factor is applied.

4. Application of Failure Rate Tables

Tables XX and XXII have been constructed for estimating the rate of random, i.e., accidental, catastrophic failures which may be anticipated in new design work. It is not intended that specific wearout life information be derived from these tables. The data used for constructing these tables were obtained from systems in their useful operating life period and do not include any wearout period information.

## D. AVERAGE DISCRETE PART FAILURE RATES, RELATIONSHIPS, RATIOS, AND ENHANCEMENT FACTORS

An analysis has been performed on the total quantity of storage and dormant operating data available on electronic parts in order to establish average part failure rates, relationships, ratios, and enhancement factors between the various part classes by type of failure.

1. Average Storage and Dormant Operating Electronic Part Failure Rates

The average observed storage and dormant operating part failure rates for all electronic discrete parts can be determined based on the data contained in Tables V through XI. Table XXIII presents these average failure rates by parts classification. Some of the failure rates are based on a small quantity of data taken primarily from one type of part. Those failure rates so indicated are to be used with caution.

2. Observed Electronic Part Failure Rate Ratios Within Part Classes

Based upon Table XXIII, the ratios within each electronic part class can be determined between catastrophic and drift failures and between dormant operating and storage failures. Table XXIV presents some of the more useful ratios. Some of the ratios are based on a small quantity of data taken primarily from one type of part. Those ratios so indicated are to be used with caution.

3. Reliability Enhancement Factors

In an attempt to determine how much reliability improvement in electronic parts can be attained through the use of higher classes of parts, a nomograph, Figure 4, has been constructed based upon military standard parts. The enhancement factors for the operating, dormant operating, and storage modes have been plotted using the best information available and estimates the reliability enhancement factor mode. Table XXV lists these factors.

TABLE XXIII

Observed Part Failure Rates by Part Classes
(Electronic Parts Only)

| | Average Part Failure Rates Fits | | | |
|---|---|---|---|---|
| | Storage | | Dormant Operating | |
| Part Class | Catastrophic A | Drift B | Catastrophic C | Drift D |
| 1 Commercial | < 30*† | 974† | No data | No data |
| 2 Military standard | 3.0 | 2.0 | 93† | < 16*† |
| 3 Selected military standard | 2.6 | No data | 83† | < 4.2*† |
| 4 High reliability | 0.39 | No data | 1.25 | No data |

*Assumes one failure
†Represents less than 1 percent of total data and primarily on one type of part.

TABLE XXIV

Observed Failure Ratios by Parts Class
(Electronic Parts Only)

| Part Class | $\lambda$ Storage Cat / $\lambda$ Storage Drift E | $\lambda$ Dor Op Cat / $\lambda$ Dor Op Drift F | $\lambda$ Dor Op Cat / $\lambda$ Storage Cat G |
|---|---|---|---|
| 1 Commercial | No data | No data | No data |
| 2 Military standard | 1.5 | > 5.8/1*† | 17/1† |
| 3 Selected military standard | No data | > 20/1*† | 32/1† |
| 4 High reliability | No data | No data | 3.2/1 |

*Assumes one failure
†Represents less than 1 percent of total data and primarily on one type of part.

TABLE XXV

Estimated Reliability Enhancement Factors for Various Part Classes
Over Military Standard Parts
(Electronic Parts Only)

| | Estimated Reliability Enhancement Factors | | |
|---|---|---|---|
| | Operating | Dormancy | Storage |
| 2 Military standard | 1 | 1 | 1 |
| 3 Selected military standard | 5-20 | 3.0-7.7 | 2.0-3.8 |
| 4 High reliability | 30-75 | 12.0-22.6 | 5.2-7.7 |

Table XXV shows the potential increase in reliability by use of different part classes. For instance use of high reliability parts will decrease storage failure by 5.2 to 7.7, dormancy failures by 12.0 to 22.6, and operating failures by 30 to 75 times. Table XXV can also be normalized to any parts class shown in order to make comparisons other than to military standard parts.

## E. AVERAGE SYSTEM FAILURE RATES, FACTORS, AND GROWTH ANALYSIS

An analysis was performed on the nonoperating data observed for thirteen separate and distinct systems to determine reliability growth, nonoperating system failure rates, and factors.

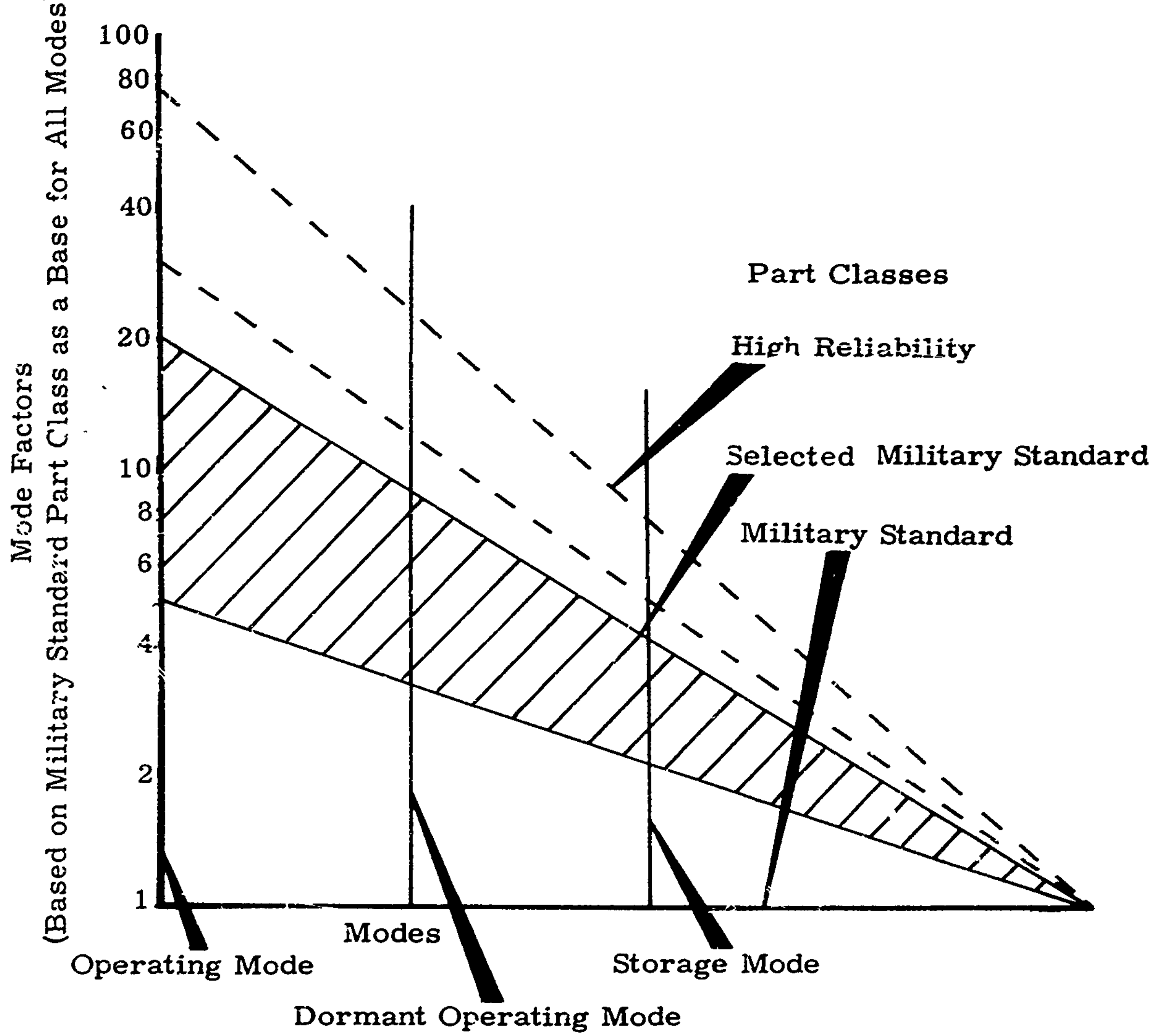



Figure 4. Reliability Enhancement Mode Factor Nomograph

1. Average System Failure Rates

Using data from thirteen electronic systems, Table XXVI was constructed to determine nonoperating failure rates by different classes and types of parts.

2. Nonoperating System Part Factors

By normalizing the average nonoperating system part failure rates of Table XXVI to block 4A of the table, the relative system nonoperating factors can be determined by the following matrix.

| | | Part Type | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Storage | | | | Dormancy | | | |
| | | A | B | C | D | E | F | G | H |
| Part Class | 1 | * | * | * | * | * | * | * | * |
| | 2 | 6.8 | 10.0 | 11.8 | 18.0 | * | * | * | * |
| | 3 | 4.5 | 4.5 | * | * | * | * | * | * |
| | 4 | 1.0 | 1.0 | * | * | 2.0 | 2.0 | * | * |

*No data available to determine factor

The factors in the matrix are in descending order for each column and ascending order for each row. These indicate the relative severity of the modes and reliability improvement achieved on systems using a better class of parts. Some factors not presently available in the matrix can be reasonably estimated. These estimates can be utilized until actual data become available.

3. Reliability Growth for Stored Electronic Systems Utilizing Military Standard Parts

Figures 5, 6, and 7 show the system catastrophic storage failure rates versus the system activation year. Regression line analysis of the data has been utilized in order to determine trends. The calculations for each regression and correlation factor follow Figures 5, 6, and 7.

The determination of regression lines and correlation factors is as follows.

TAB

Determination of Average Nonoperating Syst
Type of Parts for Storage

| Part Class | Storage Mode | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Electronic Parts | | | | | | Electronic and Electr | | |
| | Catastrophic Failure Data A | | | Total Failure Data B | | | Catastrophic Failure Data C | | |
| | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) |
| 1. Commercial | * | | * | * | | * | * | | * |
| 2. Military standard | a | 2.3 | 36.64 | a | 2.3 | 36.64 | c | 3.5 | 0.85 |
| | b | 3.5 | 7.19 | c | 5.0 | 7.19 | a | 3.9 | 37.64 |
| | c | 3.8 | 0.80 | b | 12.0 | 0.80 | d | 4.8 | 2.73 |
| | d | 4.8 | 2.50 | d | 22.7 | 2.50 | e | 4.9 | 0.20 |
| | e | 5.9 | 0.17 | e | 23.5 | 0.17 | b | 8.5 | 8.69 |
| | $\overline{X}_w$ | 2.7 | 47.30 | $\overline{X}_w$ | 4.0 | 47.30 | $\overline{X}_w$ | 4.7 | 50.11 |
| 3. Select military standard | f | 1.0 | 3.06 | f | 1.0 | 3.06 | * | | * |
| | g | 1.9 | 41.17 | g | 1.9 | 41.17 | | | |
| | h | <2.0† | 0.53 | h | <2.0† | 0.53 | | | |
| | i | <2.4† | 0.41 | i | <2.4† | 0.41 | | | |
| | $\overline{X}_w$ | 1.8 | 45.17 | $\overline{X}_w$ | 1.8 | 45.7 | | | |
| 4. High reliability | k | 0.4 | 189.90 | k | 0.4 | 189.9 | k | | * |

*No data available

†Assumes one failure

A

B

TABLE XXVI

on of Average Nonoperating System Part Failure Rates by Different Classes and Type of Parts for Storage and Dormant Operating Modes

| rage Mode | | | | | | | Dormant Operating Mo | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Electronic and Electromechanical Parts | | | | | | Electronic Parts | | | | | | Ele | |
| | Catastrophic Failure Data C | | | Total Failure Data D | | | Catastrophic Failure Data E | | | Total Failure Data F | | | Cat Fai | |
| urs nce ) | Sys-tem | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | Sys-tem | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | Sys-tem | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | Sys-tem | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | Sys-tem | Fai Ra (fi |
| | * | | * | * | | * | * | | * | * | | * | * | |
| | c | 3.5 | 0.85 | a | 4.0 | 37.64 | * | | * | | | * | | |
| | a | 3.9 | 37.64 | c | 5.9 | 0.85 | | | | | | | | |
| | d | 4.8 | 2.73 | b | 16.0 | 8.69 | | | | | | | | |
| | e | 4.9 | 0.20 | d | 22.7 | 2.73 | | | | | | | | |
| | b | 8.5 | 8.69 | e | 24.7 | 0.20 | | | | | | | | |
| | $\overline{X}_w$ | 4.7 | 50.11 | $\overline{X}_w$ | 7.2 | 50.11 | | | | | | | | |
| | * | | * | * | | * | | | * | | | * | | |
| | k | | * | k | | * | j | <0.7† | 2.79 | j | <0.7† | 2.79 | j | |
| | | | | | | | l | 0.8 | 430.04 | l | 0.8 | 430.04 | l | |
| | | | | | | | m | 21.0 | 7.04 | m | 21.0 | 7.04 | m | |
| | | | | | | | $\overline{X}_w$ | 0.8 | 439.87 | $\overline{X}_w$ | 0.8 | 439.87 | | |

B

C

Classes and

| Dormant Operating Mode | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electronic Parts | | | | | | Electronic and Electromechanical Parts | | | | | | |
| tastrophic ilure Data E | | Total Failure Data F | | | | Catastrophic Failure Data G | | | Total Failure Data H | | | |
| λ ilure ate its) | Part-Hours Experience (x $10^9$) | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | System | λ Failure Rate (fits) | Part-Hours Experience (x $10^9$) | | |
| | * | * | | * | * | | * | * | | * | | |
| | * | | | * | | | * | | | * | | |
| | * | | | * | | | * | | | * | | |
| 0.7† | 2.79 | j | <0.7† | 2.79 | j | | * | j | | * | | |
| 0.8 | 430.04 | l | 0.8 | 430.04 | l | | * | l | | * | | |
| 1.0 | 7.04 | m | 21.0 | 7.04 | m | | * | m | | * | | |
| 0.8 | 439.87 | $\overline{X}_w$ | 0.8 | 439.87 | | | | | | | | |

C

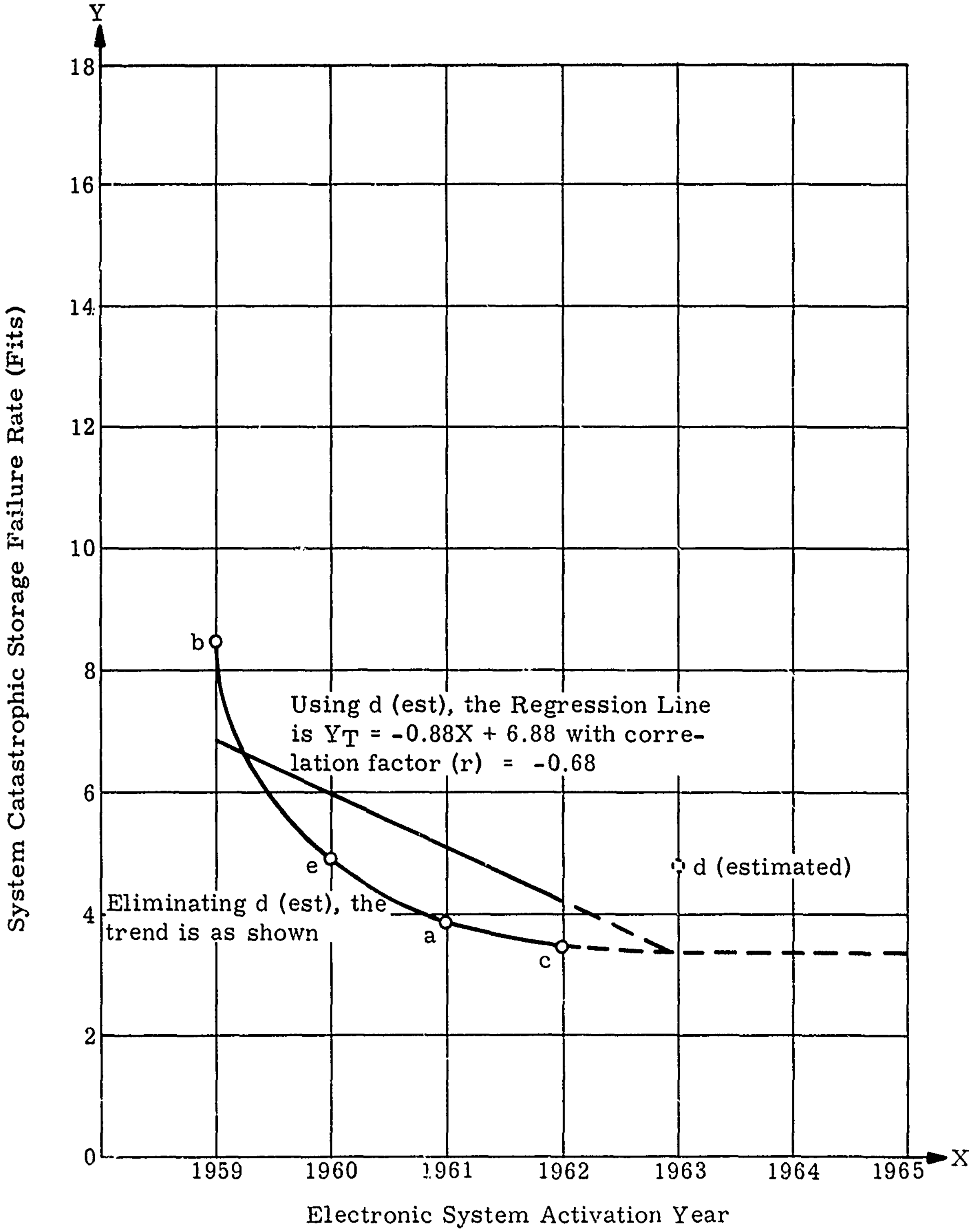



Figure 5. Electronic and Electromechanical Military Standard Part Reliability Growth for Stored Electronic Systems

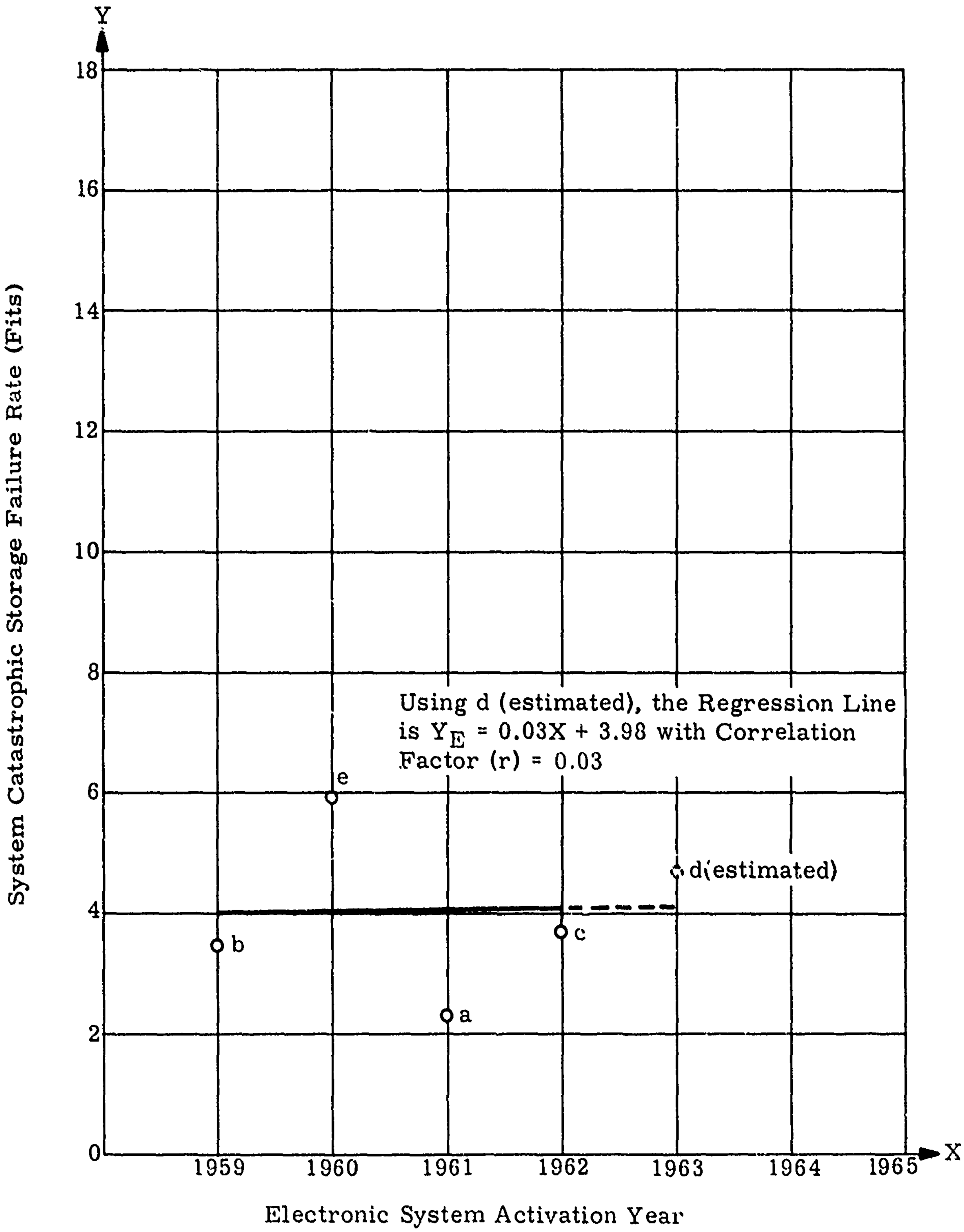
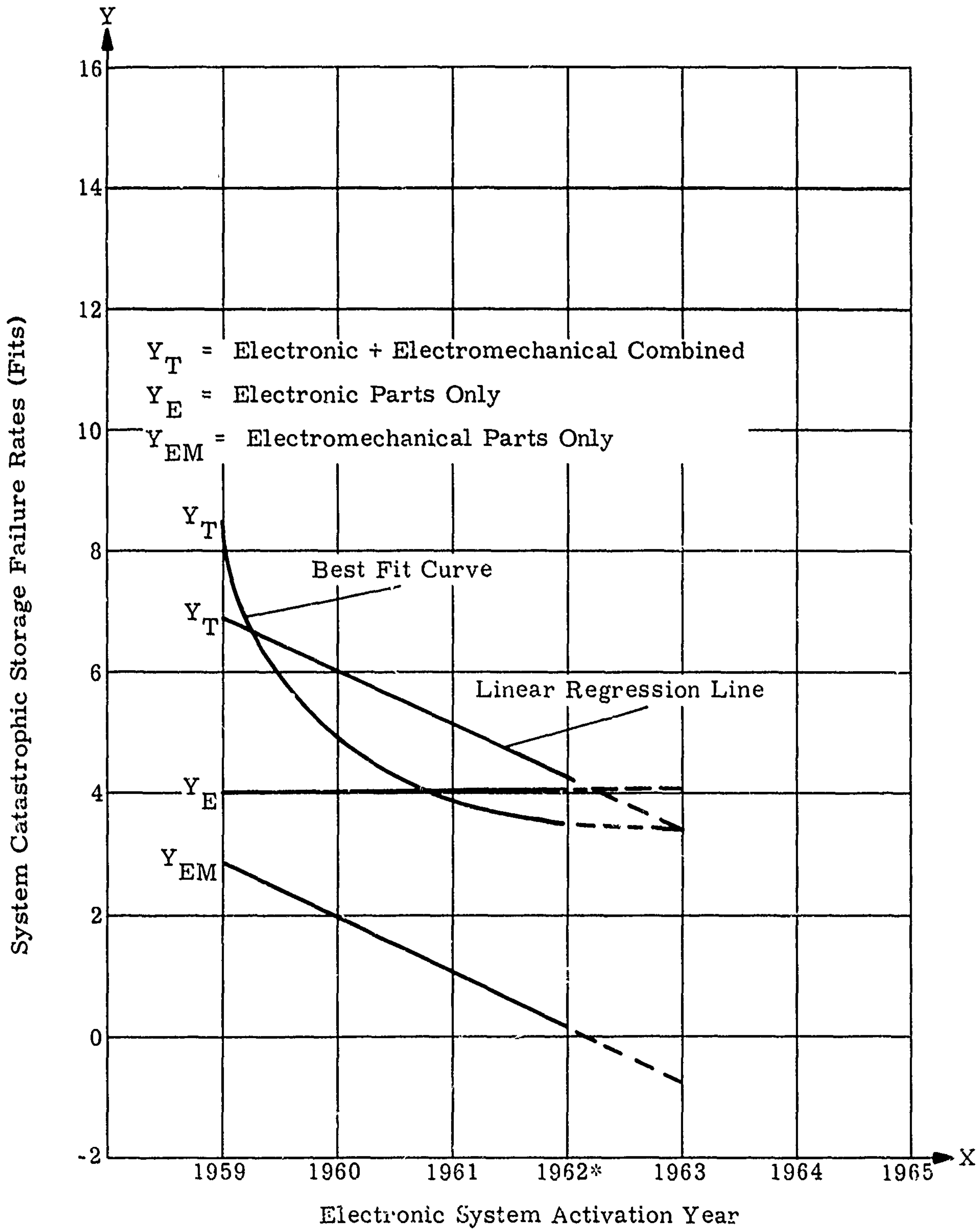



Figure 6. Electronic Military Standard Part Reliability Growth for Stored Electronic Systems




* Note: Use of linear regression lines as indicators for $Y_{EM}$ and $Y_T$ after 1962 is invalid, because each line approaches its limiting value.

Figure 7. Reliability Growth Comparison for Military Standard Parts by Part Type for Stored Electronic Systems

a. Regression Line ($Y_T$) for Electronic and Electromechanical Parts

| X* | Y† | XY | $X^2$ | $Y^2$ |
|---|---|---|---|---|
| 0 | 8.5 | 0.0 | 0 | 73.10 |
| 1 | 4.9 | 4.9 | 1 | 24.10 |
| 2 | 3.9 | 7.8 | 4 | 15.21 |
| 3 | 3.5 | 10.5 | 9 | 12.25 |
| 4. | 4.8 | 19.2 | 16 | 23.04 |
| Σ 10 | 25.6 | 42.4 | 30 | 147.70 |

*X = 0 at 1959
†Y = 0 at 0 Fits

$$m = \frac{\Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{N}}{\Sigma X^2 - \frac{(\Sigma X)^2}{N}} = \frac{42.4 - \frac{(10)(25.6)}{5}}{30 - \frac{10^2}{5}} = \frac{42.4 - 51.2}{30-20} = \frac{-8.8}{10}$$

$$m = -0.88$$

$$c = \frac{(\Sigma X)(\Sigma XY) - (\Sigma Y)(\Sigma X^2)}{(\Sigma X)^2 - N(\Sigma X^2)} = \frac{(10)(42.4) - (25.6)(30)}{10^2 - 5(30)} = \frac{424 - 768}{100 - 150} = \frac{344}{50}$$

$$c = 6.88$$

$$Y_T = m X + c$$

$$Y_T = -0.88X + 6.88.$$

b. Correlation Factor Determination ($r_T$) Electronic and Electromechanical Parts

$$r = \frac{\frac{1}{N}(\Sigma XY) - (\overline{X})(\overline{Y})}{(\sigma_X)(\sigma_Y)}$$

$$\overline{X} = \frac{\Sigma X}{N} = \frac{10}{5} = 2.00 \qquad \overline{Y} = \frac{\Sigma Y}{N} = \frac{25.6}{5} = 5.12$$

$$\frac{1}{N}(\Sigma XY) = \frac{1}{5}(42.4) = 8.48$$

$$\sigma_X^{\ 2} = \frac{1}{N}(\Sigma X^2) - (\overline{X})^2 = \frac{1}{5}(30) - 2^2 = 6.00 - 4.00 = 2.00$$

$$\sigma_X = \sqrt{2} = 1.414$$

$$\sigma_Y^{\ 2} = \frac{1}{N}(\Sigma Y^2) - (\overline{Y})^2 = \frac{1}{5}(147.70) - (5.12)^2 = 29.54 - 26.21 = 3.33$$

$$\sigma_Y = 1.825$$

$$r_T = \frac{(8.48) - (2.00)(5.12)}{(1.414)(1.825)} = \frac{-1.76}{2.58} = -0.68$$

c. Regression Line ($Y_E$) for Electronic Parts Only

| X* | Y* | XY | $X^2$ | $Y^2$ |
|---|---|---|---|---|
| 0 | 3.5 | 0 | 0 | 12.25 |
| 1 | 5.9 | 5.9 | 1 | 34.81 |
| 2 | 2.3 | 4.6 | 4 | 5.29 |
| 3 | 3.8 | 11.4 | 9 | 14.44 |
| 4 | 4.7 | 18.8 | 16 | 22.09 |
| Σ10 | 20.2 | 40.7 | 30 | 88.88 |

$$m = \frac{40.7 - \frac{(10)(20.2)}{5}}{30 - \frac{10^2}{5}} = \frac{40.7 - 40.4}{30 - 20} = \frac{0.3}{10} = 0.03$$

$$c = \frac{10\,(40.7) - 20.2\,(30)}{10^2 - 5\,(30)} = \frac{407 - 606}{100 - 150} = \frac{199}{50} = 3.98$$

$$Y_E = 0.03\,X + 3.98$$

d. Correlation Factor Determination ($r_E$) Electronic Parts

$$\overline{X} = \frac{10}{5} = 2.00 \qquad \overline{Y} = \frac{20.2}{5} = 4.04$$

$$\frac{1}{N}(\Sigma XY) = \frac{1}{5}(40.7) = 8.14$$

$$\sigma_X^2 = \frac{1}{5}(30) - 2^2 = 2.00 \qquad \sigma_X = 1.414$$

$$\sigma_Y^2 = \frac{1}{5}(88.88) - 4.04^2 = 17.77 - 16.32 = 1.45 \qquad \sigma_Y = 1.20$$

$$r_E = \frac{8.14 - 2.00\,(4.04)}{(1.414)\,(1.20)} = \frac{0.06}{1.69} = 0.03$$

e. Regression Line ($Y_{EM}$) for Electromechanical Parts Only

$$\begin{aligned} Y_T &= -0.88X + 6.88 \\ -Y_E &= -0.03X - 3.98 \\ \hline Y_T - Y_E = Y_{EM} &= -0.91X + 2.90 \end{aligned}$$

Based upon the data trends shown in Figure 5, no significant improvement in catastrophic storage failure rates for electronic and electromechanical parts should be anticipated for a weapon system utilizing a military standard class of parts and activated after 1963.

Based upon the linear regression line of Figure 6, electronic military standard parts have exhibited no discernable improvement in their catastrophic storage failure rates from 1959 to 1964. After 1962, the use of the $Y_{EM}$ and $Y_T$ linear regression lines as indicators is invalid. They are invalid because their respective Y values (as X increases) approach their respective limiting conditions to which each regression line must be asymptotic.

Based upon the comparison of the linear regression lines in Figure 7, military standard electromechanical parts have exhibited a discernable improvement in catastrophic storage failure rates from 1959 to 1962.

For the combination of electronic and electromechanical military standard parts, the catastrophic storage failure rate data have exhibited a good fit by both graphic and linear regression analysis methods from 1959 to 1962. For the electronic military standard parts, the catastrophic storage failure rate data have not exhibited a good fit by either the graphic or linear regression analysis methods from 1959 to 1964.

## Section 5

## RELIABILITY MODELS

Reliability models have been developed to make realistic weapon system concept decisions that will result in achieving required reliability. These models are used to predict mission reliability and to determine the maximum duration of storage or dormant operation that a system can withstand and still meet its reliability goal. After the model has been completed and the necessary calculations are made, it may be found that the system under consideration cannot meet its goal after a required storage or dormant operating period. In this case, improved reliability parts will have to be substituted or periodic checkout will have to be performed to upgrade reliability by detecting accumulated nonoperating failures. The optimum frequency of such checkouts, as well as the necessary capability of the test equipment to detect a given percentage of the failures, can also be determined by the mathematical model. The basic data necessary for model preparation are part nonoperating failure rates, event times, and k factors to describe application and environmental stresses.

A recent paper entitled "Reliability and Maintainability Research in the U.S. Air Force" (Reference 57) contains the following pertinent information on the subject: "The current use of nonoperating or dormant defense systems, such as Minuteman, and the expected increase in their use in the future, have dictated the need for nonoperating part failure rate data for use in predicting the reliability of these systems."

Early versions of reliability models employed operational use failure rates and ignored the much more significant failure rates in storage and dormant conditions. In a typical missile system, nonoperating time may be as much as two million times longer than operating time. Even though the operational part failure rate is normally greater than the nonoperating failure rate, it can readily be seen that the vast difference in time makes the nonoperating factor of prime importance to reliability.

To visualize the effect of nonoperating failure rates, the following simplified model is presented. The parts list shown in Table XXVII is from a noncomplex tactical electronic system.

## TABLE XXVII

### Parts List For Reliability Model

| Part Type | Quantity Used (N) | Nonoperating Fail Rate $\lambda_{NO}$* (Mil-Std) | $N\lambda_{NO}$ | Percentage of Total | Operating Fail Rate $\lambda_{op}$* (Mil-Std) | $N\lambda_{op}$ | Percentage of Total |
|---|---|---|---|---|---|---|---|
| Transistor, low power Si | 206 | 3 | 618 | 7.6 | 1,875 | 386,250 | 60.9 |
| Transistor, high power Si | 2 | 30 | 60 | 0.7 | 2,500 | 5,000 | 0.8 |
| Diode, general purpose | 179 | 1 | 179 | 2.2 | 615 | 110,085 | 17.4 |
| Diode, zener | 21 | 7 | 147 | 1.8 | 1,250 | 26,250 | 4.1 |
| Resistor, metal film | 649 | 1 | 649 | 8.0 | 93 | 60,357 | 9.5 |
| Resistor, power WW | 4 | 2 | 8 | 0.1 | 190 | 760 | 0.1 |
| Capacitor, glass | 104 | 0.2 | 20.8 | 0.3 | 10 | 1,040 | 0.2 |
| Capacitor, solid Ta | 126 | 3 | 378 | 4.6 | 102 | 12,852 | 2.0 |
| Capacitor, ceramic | 125 | 1 | 125 | 1.5 | 48 | 6,000 | 0.9 |
| Coil, RF | 108 | 50 | 5,400 | 66.3 | 200 | 21,600 | 3.4 |
| Potentiometer, WW | 1 | 5 | 5 | <0.1 | 1,130 | 1,130 | 0.2 |
| Switch, selector | 2 | 100 | 200 | 2.5 | 250 | 500 | 0.1 |
| Microcircuits | 5 | 70 | 350 | 4.3 | 400 | 2,000 | 0.3 |
| Connectors | 7 | 1 | 7 | <0.1 | 60 | 420 | 0.1 |
| | 1,539 | | 8,146.8 | 100 | | 634,244 | 100 |

*Failure rate in fits - failures X $10^{-9}$ hours

This model is applicable for systems with test equipment designs that do not degrade reliability (Section 6). Reliability analyses of many systems in use today have proven that they can conform to this concept.

After failure rates have been assigned to the parts list, the next step is to obtain a factory-to-target sequence. Figure 8 is a condensed version of such a sequence for both the no-test and test concepts.

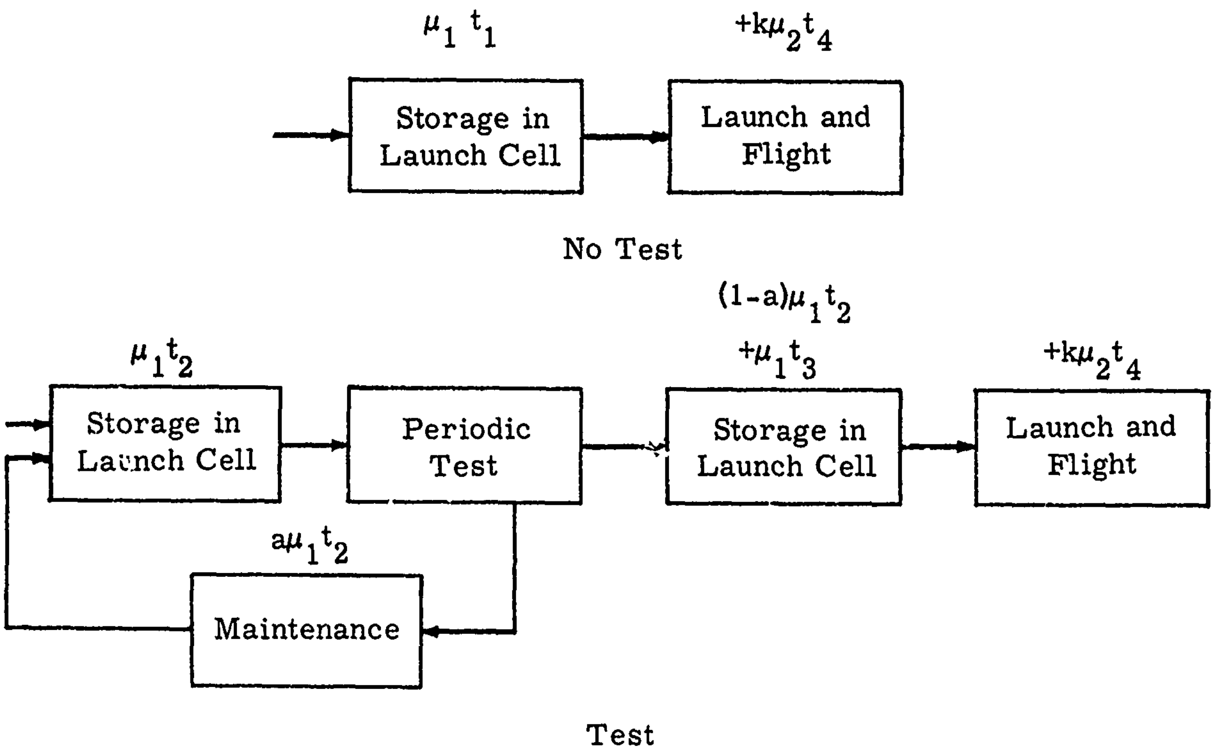



Figure 8. Factory To Target Sequence

Values for the various terms used in the reliability model are:

$a$ = 90 percent (portion of failures detected by periodic test equipment)

$t_1$ = 43,800 hours or 5 years (total nonoperating time prior to launch)

$t_2$ = 41,610 hours or 4 years, 9 months (nonoperating time up to last periodic test before launch)

$t_3$ = 2190 hours or 3 months (nonoperating time between last periodic test and launch)

$t_4$ = 0.0166 hour or 1 minute (flight time)

$\mu_1$ = 8147 fits (sum of nonoperating failure rates for 1539 missile electronic parts)

$\mu_2$ = 634,244 fits (estimated operational failure rate - values are normally obtained from sources such as MIL-HDBK-217A)

k = 1000 (factor for flight environment).

Summing up the no-test terms

$$\mu_1 t_1 = 0.357$$

$$k\mu_2 t_4 = 0.011$$

$$\lambda t = 0.368$$

$$R = e^{-0.368} = 0.692$$

it is found that this missile electronic system reliability after 5 years storage under the no-test concept would be 0.692. If periodic tests were performed every 3 months, however,

$$(1-a)\mu_1 t_2 = 0.034$$

$$\mu_1 t_3 = 0.018$$

$$k\mu_2 t_4 = 0.011$$

$$\lambda t = 0.063$$

$$R = e^{-0.063} = 0.939$$

the same missile electronic system reliability after 5 years storage would be 0.939.

By substituting new values for "t", decisions can be made to reflect the acceptable nonoperating durations and/or frequency of periodic checkout which will allow established reliability goals to be achieved. The effect of varying degrees of test equipment capability to detect failures (a) can also be determined. By consulting data similar to that given in Table XXVII, the parts which contribute most to failure can be pinpointed. For instance, although RF coils account for only 7 percent of the total parts used in the sample system, they can be expected to contribute 66.3 percent of the nonoperating failures. In the more detailed models, exact types of parts responsible for the problem would be uncovered by this type of part mix analysis.

Reliability models can also be used to make cost effectiveness tradeoffs between military standard and high reliability parts. A figure of merit ratio (Table XXVIII) is calculated showing decrease in failure rate divided by increase in cost to determine where it would be most advantageous to substitute high reliability parts. Many times the models will show that the amount saved by having additional "good missiles" available in operational readiness is greater than the cost increase for using selected high reliability parts. Consider a stockpile of 100 military standard part missiles which cost $20,000 per missile. Reliability after 5 years storage is only 0.69 (Figure 9), therefore, 30 missiles are not available for launch and $600,000 has been lost. By substituting high reliability parts, reliability after 5 years storage now becomes 0.93; only 7 missiles are not available for launch and a saving of $460,000 has been achieved over the previous case compared with an additional expense of $700 x 100 missiles = $70,000 for better parts. Thus, the cost effectiveness study would result in a net saving of $390,000.

The first incremental increases in reliability (Table XXIX) are great compared with the resulting small increases in cost because the technique results in the selection of the most critical parts for replacement by higher reliability part types. The same method can be used for analyzing the effects of weight, design concept, and power requirements on system reliability. This type of cost effectiveness study should be performed during Project Definition Phase of a contract so that the maximum benefits can be achieved. Figure 9 shows that for a noncomplex system, reliability improvement can be obtained with a small additional expense for high reliability parts.

## TABLE XXVIII

**Figure of Merit Ratios**

| Part Type | Qty Used (N) | $\lambda_{NO}$ Mil-Std | $\lambda_{NO}$ High Rel | $N_i \lambda_{NO_i}$ Mil-Std | $N_i \lambda_{NO_i}$ High Rel | $\Delta N_i \lambda_{NO_i}$ | Unit Cost (C) Mil Std | Unit Cost (C) High Rel | $\Delta C$ | $N\Delta C$ | $\Delta N\lambda / N\Delta C$ | Order |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transistor, low power, Si | 206 | 3 | 0.7 | 618 | 144.2 | 473.8 | 1.40 | 1.90 | 0.50 | 103.00 | 4.6 | 6 |
| Transistor, high power, Si | 2 | 30 | 3 | 60 | 6 | 54 | 82.00 | 110.00 | 28.00 | 56.00 | 1.0 | 10 |
| Diode, general purpose | 179 | 1 | 0.3 | 179 | 53.7 | 125.3 | 0.78 | 2.00 | 1.22 | 218.38 | 0.6 | 11 |
| Diode, zener | 21 | 7 | 1 | 147 | 21 | 126 | 1.10 | 2.90 | 1.80 | 37.80 | 3.3 | 7 |
| Resistor, metal film | 649 | 1 | 0.2 | 649 | 129.8 | 519.2 | 0.29 | 0.31 | 0.02 | 12.98 | 40.0 | 2 |
| Resistor, power WW | 4 | 2 | 0.2 | 8 | 0.8 | 7.2 | 1.80 | 2.50 | 0.70 | 2.80 | 2.6 | 8 |
| Capacitor, glass | 104 | 0.2 | 0.05 | 20.8 | 5.2 | 15.6 | 1.50 | 1.90 | 0.40 | 41.60 | 0.4 | 12 |
| Capacitor, solid Ta | 126 | 3 | 0.2 | 378 | 25.2 | 352.8 | 0.60 | 1.10 | 0.50 | 63.00 | 5.6 | 4 |
| Capacitor, ceramic | 125 | 1 | 0.2 | 125 | 25 | 100 | 0.70 | 1.20 | 0.50 | 62.50 | 1.6 | 9 |
| Coil, RF | 108 | 50 | 10 | 5400 | 1080 | 4320 | 0.40 | 1.00 | 0.60 | 64.80 | 66.6 | 1 |
| Potentiometer, WW | 1 | 5 | 5 | 5 | 5 | - | 6.00 | 12.00 | 6.00 | 6.00 | - | 13 |
| Switch, selector | 2 | 100 | 50 | 200 | 100 | 100 | 3.00 | 12.00 | 9.00 | 18.00 | 5.5 | 5 |
| Microcircuits | 5 | 70 | 10 | 350 | 50 | 300 | 45.00 | 52.00 | 7.00 | 35.00 | 8.6 | 3 |
| Connectors | 7 | 1 | 1 | 7 | 7 | - | 2.00 | 3.00 | 1.00 | 7.00 | - | 14 |

## TABLE XXIX

Cost Effectiveness Study

| Ordered Part Type | Order | $\Delta N_i \lambda_{NO_i}$ | λ System Decrease | Cost | Cumulative Cost | Nλ t | 5 Year Storage R |
|---|---|---|---|---|---|---|---|
| | | | 8146.8 | | | 0.357 | 0.692 |
| Coil, RF | 1 | 4320 | 3826.8 | 64.80 | 64.80 | 0.168 | 0.845 |
| Resistor, metal film | 2 | 519.2 | 3307.6 | 12.98 | 77.78 | 0.145 | 0.865 |
| Microcircuits | 3 | 300 | 3007.6 | 35.00 | 112.78 | 0.132 | 0.876 |
| Capacitor, solid, Ta | 4 | 352.8 | 2654.8 | 63.00 | 175.78 | 0.116 | 0.890 |
| Switch, selector | 5 | 100 | 2554.8 | 18.00 | 193.78 | 0.112 | 0.894 |
| Transistor, low power, Si | 6 | 473.8 | 2081.0 | 103.00 | 296.78 | 0.091 | 0.913 |
| Diode, zener | 7 | 126 | 1955.0 | 37.80 | 334.58 | 0.086 | 0.918 |
| Resistor, power, WW | 8 | 7.2 | 1947.8 | 2.80 | 337.38 | 0.085 | 0.919 |
| Capacitor, ceramic | 9 | 100 | 1847.8 | 62.50 | 399.88 | 0.081 | 0.922 |
| Transistor, high power, Si | 10 | 54 | 1793.8 | 56.00 | 455.88 | 0.079 | 0.924 |
| Diode, general purpose | 11 | 125.3 | 1668.5 | 218.38 | 674.26 | 0.073 | 0.930 |
| Capacitor, glass | 12 | 15.6 | 1652.9 | 41.60 | 715.86 | 0.072 | 0.931 |
| Potentiometer, WW | 13 | - | 1652.9 | 6.00 | 721.86 | 0.072 | 0.931 |
| Connectors | 14 | - | 1652.9 | 7.00 | 728.86 | 0.072 | 0.931 |

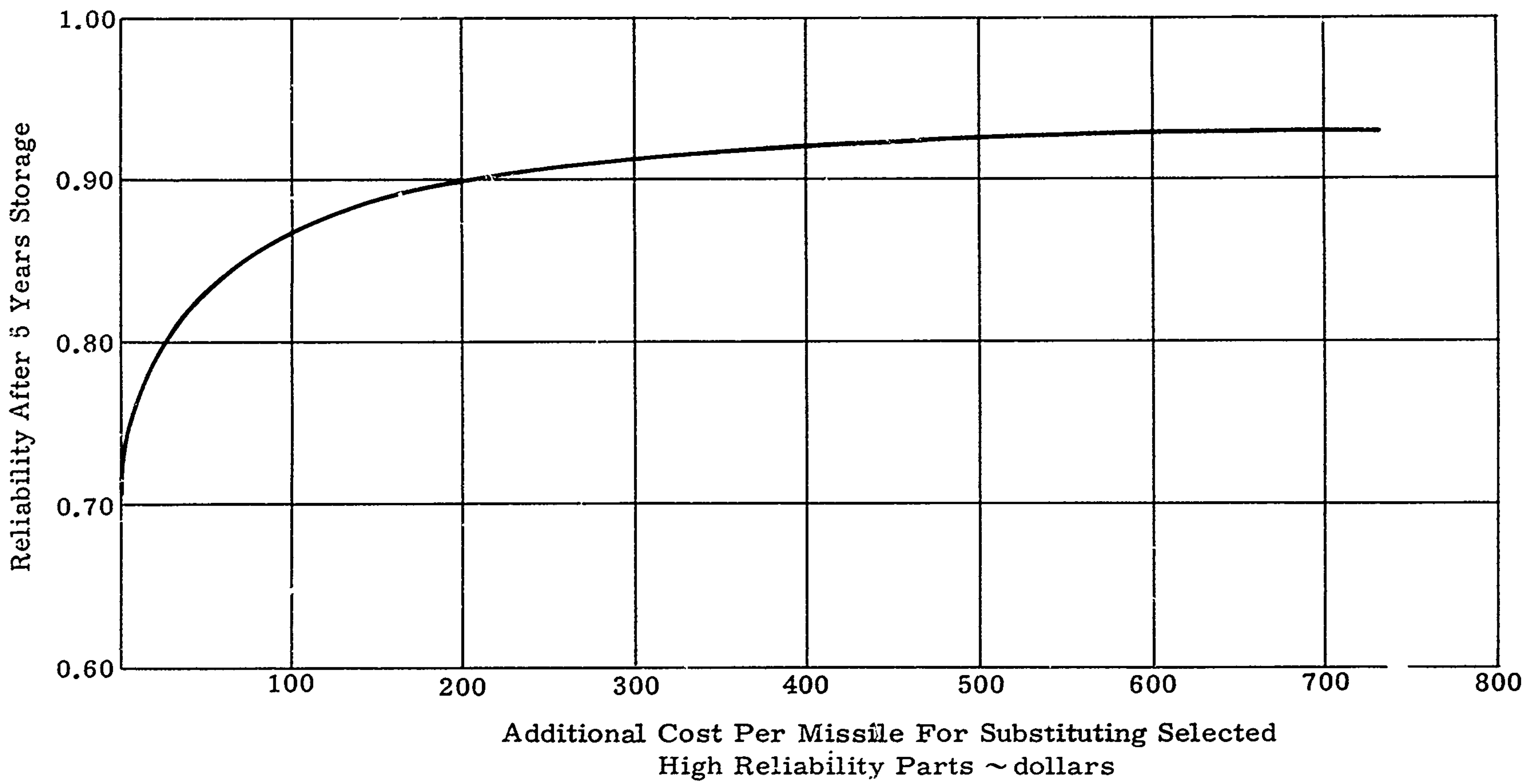



Figure 9. Cost Effectiveness

## Section 6

## CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

#### 1. Nonoperating Failure Rates and Factors

It has been established that electronic part failure rates in the nonoperating mode are essentially the same over many different systems and programs. This finding has resulted in the concept that the nonoperating failure rates for electronic parts represent a baseline and that changes from this baseline failure rate due to such factors as electrical stresses, application tolerance margins, mission environments, and parts screening programs can now be established with an accuracy previously unattainable. This represents a major step forward in the capability to design new systems and to control reliability during the manufacturing and utilization phases. Potentially, it also represents the most important advance in reliability prediction techniques since the publication of RCA's TR 1100 (currently issued as MIL-HDBK-217A).

The ratio of average nonoperating storage failure rates between military standard and high reliability types is now about 8 to 1 based on the data shown in Section 4D, Table XXV. The average part failure rate in the dormant operating mode with about 10 percent of rated power applied is about 3 times greater than the failure rate for the same class parts in storage. When comparing MIL-HDBK-217A data to the failure rates developed by this program, the average military standard operating to nonoperating failure rate ratio for the systems studied was found to be 99 to 1. However, individual differences ranged from 13 to over 150 to 1. A primary reason for variations of this ratio is the different kind of part complement which is found in each system. For example, if a system contains a large percentage of parts with a high operating to nonoperating ratio, the system ratio will be high. On the other hand, a system whose parts are severely derated will have a lower operating to nonoperating ratio. The effects of part complement can be seen in Table XXX. Actual data was used in the table but for the purposes of this report, systems were designated A, B, and C.

TABLE XXX

Effect of Part Complement

| High Usage Mil-Std Part Type | Mil-Hdbk-217A† 50%, 25°C Operating Failure Rate* | Nonoperating‡ Failure Rate* | Part Ratio Op/No | Percent of Part Complement for System | | |
|---|---|---|---|---|---|---|
| | | | | A | B | C |
| Resistor, metal film | 140 | 1 | 140 | 23 | 45 | 44 |
| Resistor, carbon composition | 3.5 | 0.1 | 35 | - | 10 | - |
| Resistor, power wirewound | 19 | 2 | 9.5 | 15 | 6 | 1 |
| Capacitor, tantalum, solid | 34 | 3 | 11.3 | 2 | 6 | 9 |
| Capacitor, glass | 10 | 0.2 | 50 | 1 | 8 | 7 |
| Capacitor, ceramic | 24 | 1 | 24 | 6 | 2 | 9 |
| Transistor, med pwr, Si planar | 820 | 10 | 82 | 4 | 3 | 1 |
| Transistor, low pwr, Si planar | 410 | 3 | 137 | 8 | 10 | 14 |
| Diodes, med pwr, Si | 900 | 3 | 300 | 6 | 2 | 2 |
| Diodes, low pwr, Si | 410 | 1 | 410 | 33 | 7 | 11 |
| Diodes, zener | 1250 | 7 | 179 | 2 | 1 | 2 |
| | System Ratio Op/No = | | | 148-1 | 78-1 | 93-1 |

* = FITS, Failure per billion hours.
† = MIL-Hdbk 217A includes both drift and catastrophic failures
‡ = This includes only catastrophic failures

A comparison of recent observed data showed that operating to non-operating failure rate ratios average about 15 to 1. Since this is much lower than the ratios shown in Table XXX, it would appear that the MIL-HDBK-217A failure rates are somewhat higher than that being experienced by present production. The same influence of improved design and production processes would also apply to individual part ratios where over the past 4 years screened high reliability parts have shown a 100 to 1 improvement. Microcircuits as a class have low operate to nonoperate ratios with a ratio of about 4 to 1 for operate and 2 to 1 for dormant operation.

Present day prediction methods for electronic systems (References 59 and 60) incorporate electrical stress, temperature stress, and use environment. This program has shown, however, that such factors as parts screening techniques, tolerance margins in application of parts, and the design of test and checkout equipment have a greater influence over part failure rates in operational use (Reference 69).

The frequency of electronic part failures can be correlated with non-operating as well as operating time periods. This does not imply that either is the cause of failures, but rather that time and the operating stresses may be viewed as accelerating or precipitating factors in the basic failure mechanisms.

It should be noted that for the 76 billion part-hours of observed military standard data, the application and part class effects are such as to mask out the effects of cyclic temperature stresses over the ranges experienced. This indicates that the use of precise temperature control in the nonoperating mode to reduce failure frequency would not be as effective as control of other stresses such as location, packaging, handling, and shipping which have demonstrated a definite influence on the nonoperating mode failure rates.

The acceleration factor for basic failure mechanisms is recognized as being the lowest for conditions of controlled storage because in controlled storage many of the operating stresses are either eliminated or reduced. This is proved by actual field experience as shown in Section 4. Thus, the present practice of using laboratory operating conditions as the basic reference point to determine acceleration factors is questionable because operating parts are subjected to a wider range and variety of stresses and factors which result in a lack of data agreement between the part failure rates observed from different systems.

A significant finding is that the average catastrophic part system failure rate under nonoperating conditions varied from 3.5 to 8.5 fits per part (a range of 5.0 fits) for five distinctly different missile electronic systems

which utilized only a military standard class of parts and were stored in depot areas throught the world. Since the range of observed nonoperating failure rates is very small for the same class of parts under storage, this data agreement strongly supports the theory that a failure rate baseline could be established for various part classes in the nonoperating state. It is also felt that, because of the close agreement of the nonoperating data, the nonoperating baseline will provide a better means of determining consistent acceleration factors for the range of different operating conditions and equipment applications. Figure 10 illustrates the nonoperating failure rate baseline theory for equipment using military standard parts and gives some of the operating mode factors based on Martin Marietta experience.

The nonoperating failure rate has been shown to be important to all electronic systems observed, and this fact provides an important advance in reliability analysis. Using the average catastrophic nonoperating failure rate for electronic systems employing military standard parts of 4.7 fits/ part as calculated in Section 4, it is now possible during concept studies or contract definition phases to make simple and quick system reliability predictions, tradeoff studies, and other decisions by estimating the total number of electronic parts (complexity) in the system being analyzed. The ease of computation is comparable to the active element group prediction technique (Reference 48), but the results are believed to be more accurate. As detailed knowledge of a system becomes available, a more complex mathematical model based upon the logistic cycle, percent checkout capability, frequency of periodic tests, and specific parts list can be constructed and reliability predictions and tradeoffs refined.

For analog electronic systems utilizing military standard parts, the ratio of drift to catastrophic nonoperating failures has been calculated to be approximately 1 to 2.5. In the Martin Marietta test program (Section 3B), it is shown from the testing of printed circuit boards and the subsequent testing of each individual part from those boards that with proper circuit design the circuit parameters can be made relatively insensitive to the effects of individual part drift and cumulative drift tolerance buildup of parts within that circuit. The test program was a byproduct of other projects and as such could not be designed to answer all questions nor fill all gaps in the data.

Under ideal application conditions, i.e., properly designed digital circuits, the data indicate that the failure rate for dormant operating conditions is comparable to the nonoperating storage condition. It would appear that the dormant failure rate approaches that for nonoperating storage, but it would never be lower. However, the disadvantage of a slightly higher failure rate must be weighed against the potential advantage of dormant operation which permits continuous monitoring of the system for operational readiness.

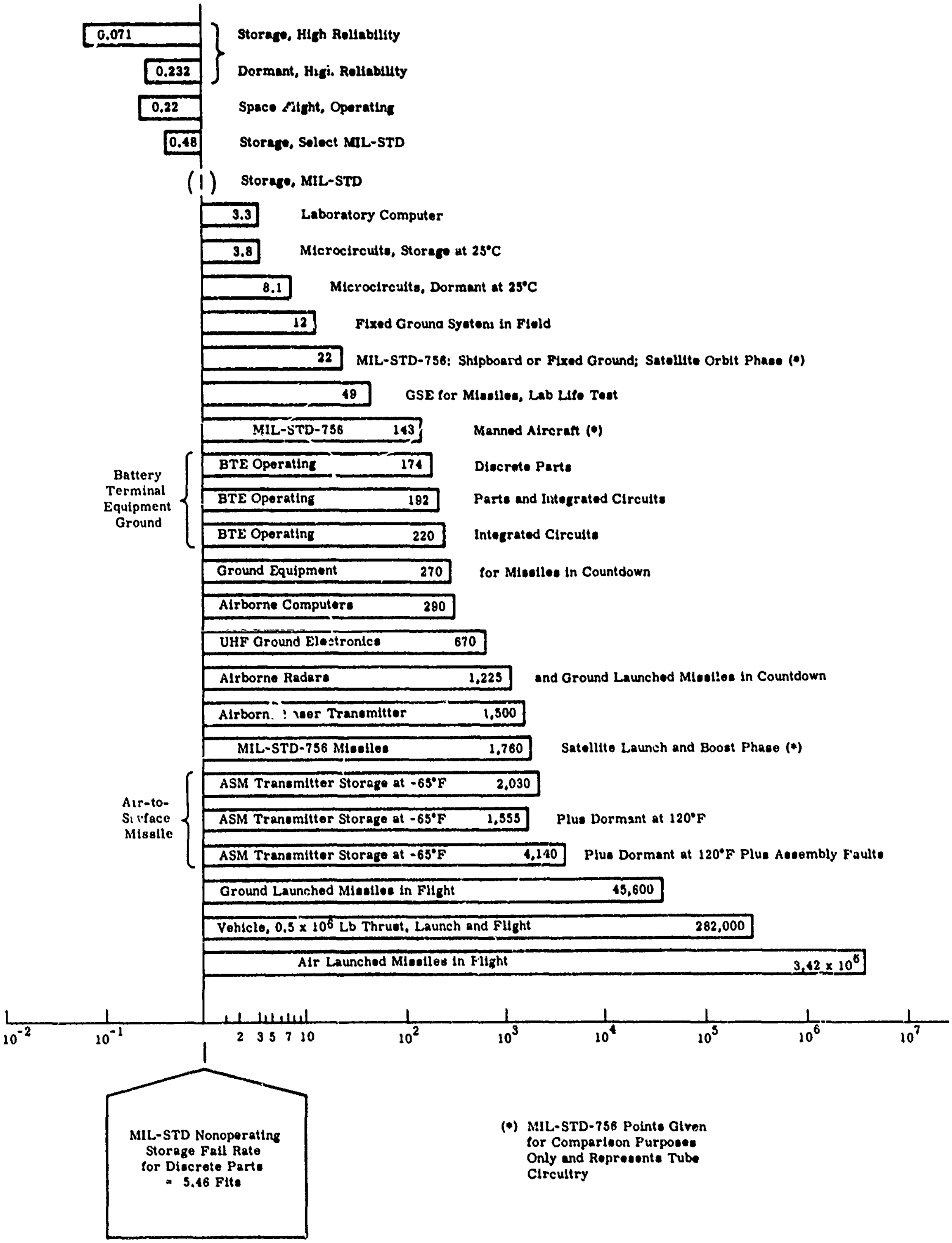



Figure 10. Application Factor Comparison by Data Sources to Nonoperating Storage, MIL-STD Electronic Parts Only in Transistor Circuits

Prior to this report it was thought and repeatedly reported that non-operating degradation data and failure rates were unavailable, nonexistent, or incomplete (References 1, 13, 28, and 35). These findings were not without basis, because the effort to locate, collect, and review potential data sources and to amass the failure rate data required the impetus of a specific study and investigation program. The sponsorship of the Rome Air Development Center was instrumental in the successful accomplishment of the project.

Based upon successful acquisition of over 750 billion part hours of experience and engineering judgment for those parts that lacked sufficient data, nonoperating mode catastrophic failure rate charts for military standard and high reliability type parts have been constructed in Section 4. The failure rates in these charts should be used for reliability modeling rather than the raw data found in Tables VI and X.

2. Nonoperating Failure Modes/Mechanisms

The failure analysis effort on parts from the Martin Marietta test program has provided information to prepare design notes that will be useful in developing parts with improved nonoperating survival capabilities. A better understanding of nonoperating failure mechanisms has been obtained and it is now possible to classify these failures into two basic types which are described in Appendix B. Most nonoperating failures are traceable to latent manufacturing defects rather than specific aging mechanisms. These defects will pass initial functional tests but finally become evident after nonoperating periods.

The electronic part nonoperating failure modes directly associated with processes and/or improper design were separated into the following percentages:

| Type | Percentage |
|---|---|
| Bonding/welding | 21.5 |
| Photoetching | 17.2 |
| Transportation and handling | 12.9 |
| Seal aging | 12.9 |
| Expansion coefficient | 12.9 |
| Conductive cement | 8.6 |
| Defective hermetic seal | 4.3 |
| Plating | 4.3 |
| Soldering | 4.3 |

Leaky seals on tantalum capacitors and process variability on integrated circuits were among the most notable problems uncovered in the laboratory.

The type of failure detected in this study strongly supports the practice that reliability can be improved by part screening. It is believed that a sizeable percentage of the failures could have been eliminated by burn-in and production environmental testing that included temperature, shock, and vibration exposure.

3. Checkout Strategy

The capability of test equipment to detect a high percentage of electronic system failures has been shown to have an important effect on reliability. Two outcomes are possible for periodic checkout-acceptance or rejection. Detailed evaluation shows, however, that only "a" percent of the existing failures are found. Undetected failures accumulate in the untested portions of a system under both operating and nonoperating conditions. As a further extension of this concept, many electronic systems have a very high proportion of nonoperating time in their life. Therefore, even though nonoperating failure rates are quite low, they will be a significant contributor to mission failures when undetected prior to use.

Improvements have been made in mathematical modeling techniques which allow tradeoffs to be made between cost and availability considerations. The effect that checkout strategy has on the reliability of different systems can be seen in Figure 11. It is possible through improper design to have a checkout capability which will degrade equipment. This situation is shown in Concept A. With a highly complex system and no periodic tests, Concept B can be used to determine whether the specified reliability requirements can be met after a prolonged period of nonoperation. Concept C describes the situation in which a system can be maintained at the required reliability by specifying the proper time between periodic tests. Concept D represents a system of low complexity with less than 300 military standard electronic parts. Such a system can maintain reasonable reliability (>0.90) over a period of 5 years with a no-test concept.

Another means to upgrade reliability of the systems subjected to periodic test is to increase the failure detection capability of the test equipment. The additional cost of this strategy must be weighed against the value of having additional good systems ready for use. It is desirable to design any system to have no checkout or maintenance (Concept D); however, to meet the operational readiness requirements specified for complex electronic systems based upon current nonoperating technology, improved parts are required or a periodic test and maintenance concept is needed If a periodic test and maintenance concept is elected, the tests should be conducted with sufficient frequency so that it is not necessary to test immediately prior to operational use. The reason for this is the possibility of test equipment malfunctions which could cause the unwanted rejection of good systems.

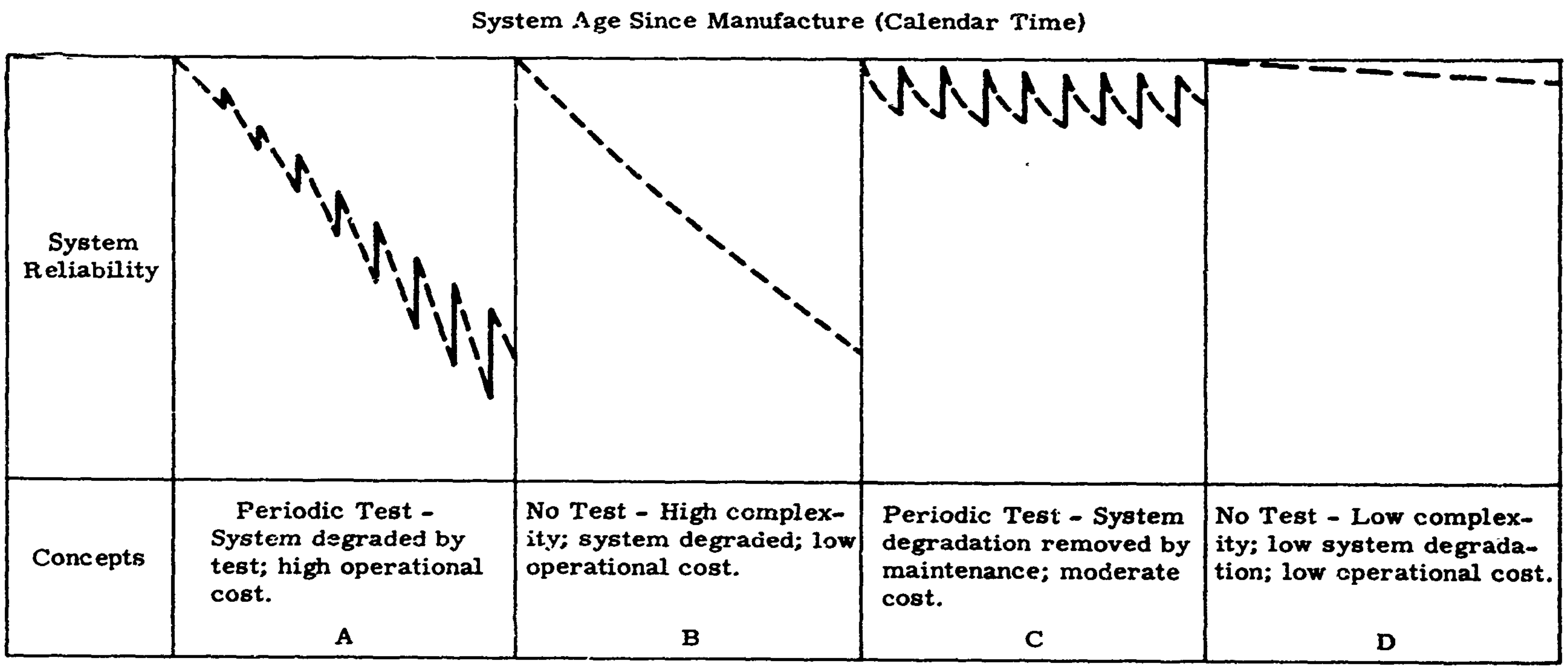



Figure 11. System Reliability versus Checkout Strategy

4. Additional Reliability Techniques for Storage Survival Capability

The failure analyses performed under this contract strongly suggest that better process control and screening are the two most important ways to achieve improved storage survival. Although there is doubt that some high reliability programs are satisfying all of their objectives, the experience of the Bell Telephone Laboratories with submarine cable repeaters (Reference 12) has proved the capability of screening and process control. On the other hand, systems are in use today which require 3 years of burn-in to eliminate infant mortality and obtain a constant failure rate. It would appear, therefore, that additional study of screening techniques should be undertaken.

5. Nonoperating Survival Prediction Methods

The rate at which electronic part failures precipitate during nonoperating periods has been adequately described by the exponential formula for four distinct systems with storage periods ranging from a few months to almost 5 years. One of these systems is described in Reference 23 which states "the most significant conclusion from a reliability analysis point of view is that storage failures conform to a Poisson process since the failure rates were observed to be constant with time. This means that the exponential distribution may be used to calculate the probability of surviving the storage mode." Figure 12 is a chart of typical data obtained from periodic tests on stockpiled missiles which shows a constant storage failure rate.

While it is well know that some parts, particularly ordnance items have an increasing failure rate with time, other parts have a decreasing failure rate with time so that a composite system will fail at a reasonably constant rate.

At the request of the Raytheon Company, Martin Marietta made a storage survival prediction of an Army tactical surface-to-air missile using mathematical modeling techniques and nonoperating failure rates. The predicted mean-time-between-failure was later found to agree closely with the actual field experience. This fact provides additional validation of the nonoperating failure rate chart.

In the case of a Navy tactical air-to-surface missile manufactured in quantity by Martin Marietta, a 5 year storage survival prediction was made using the nonoperating failure rates applied to the missile nose cone electronics. The prediction was then compared with the actual storage reliability history of these same nose cone electronics systems for a period of 54 months. Excellent agreement, within 1 percent, was observed between the prediction and actual history of operational readiness over this period.

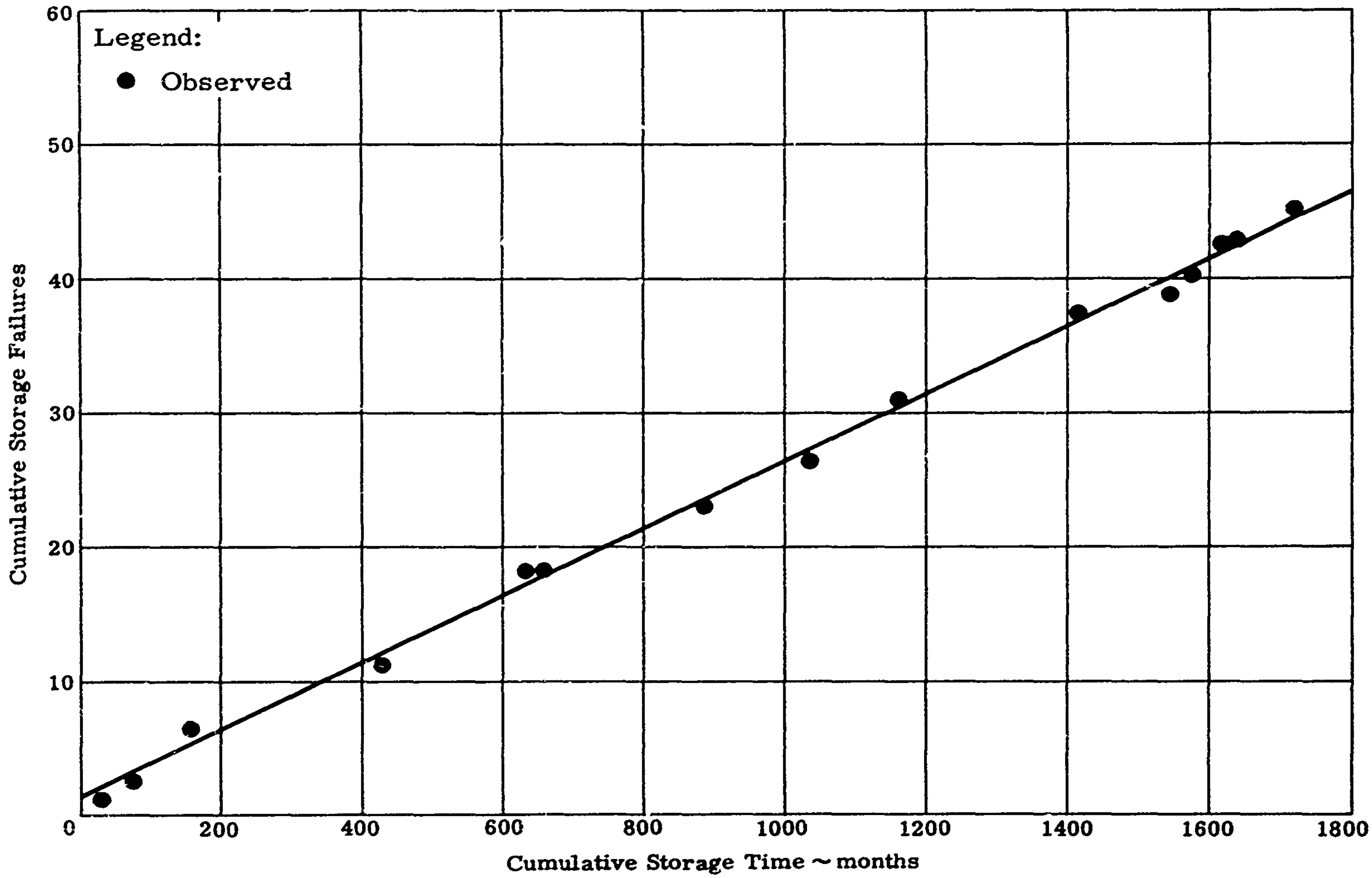



Figure 12. Storage Failures of Stockpiled Missiles

Nonoperating failure rate data were used to make a prediction for a Navy surface-to-air missile. At the end of 12 months storage the prediction was within 1.4 percent of the actual, and after 24 months storage the prediction was within 2.4 percent of the actual operational readiness as determined from data released by the U.S. Naval Fleet Missile Systems Analysis and Evaluation Group. Figures 13, 14, and 15 show the comparisons of the predicted versus the observed values for the three different systems which were studied.

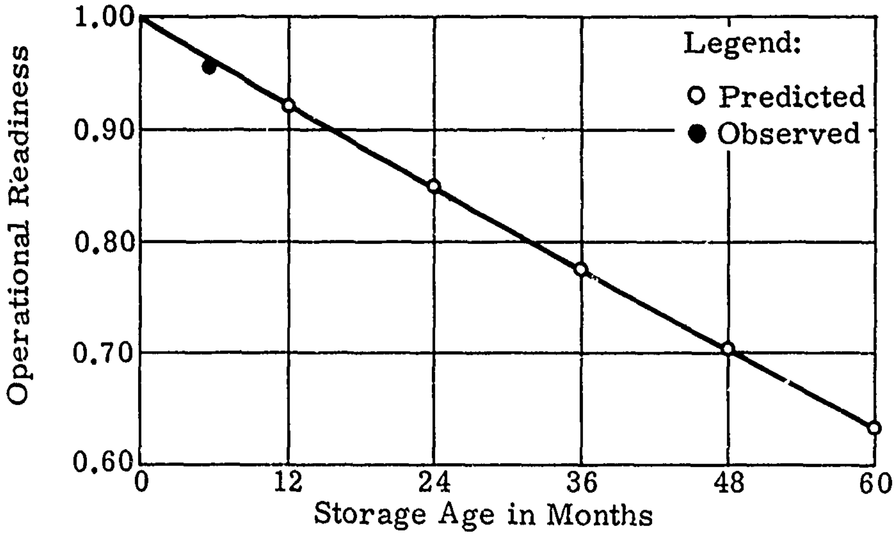



Figure 13. Surface-to-Air Missile Storage Survival

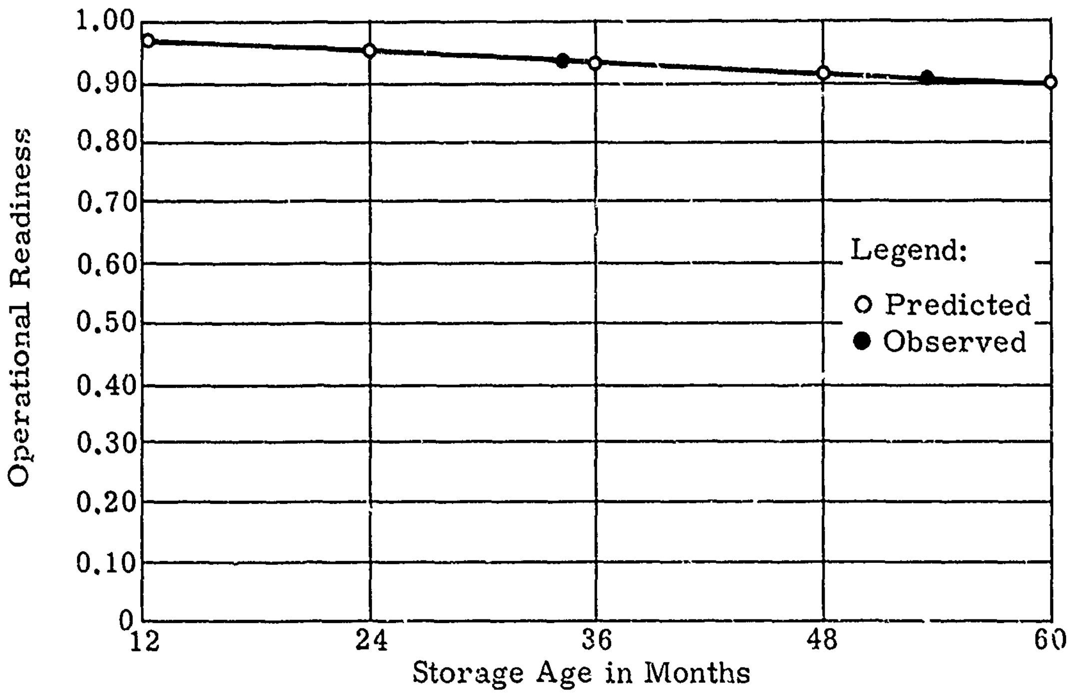



Figure 14. Air-to-Surface Missiles Storage Survival

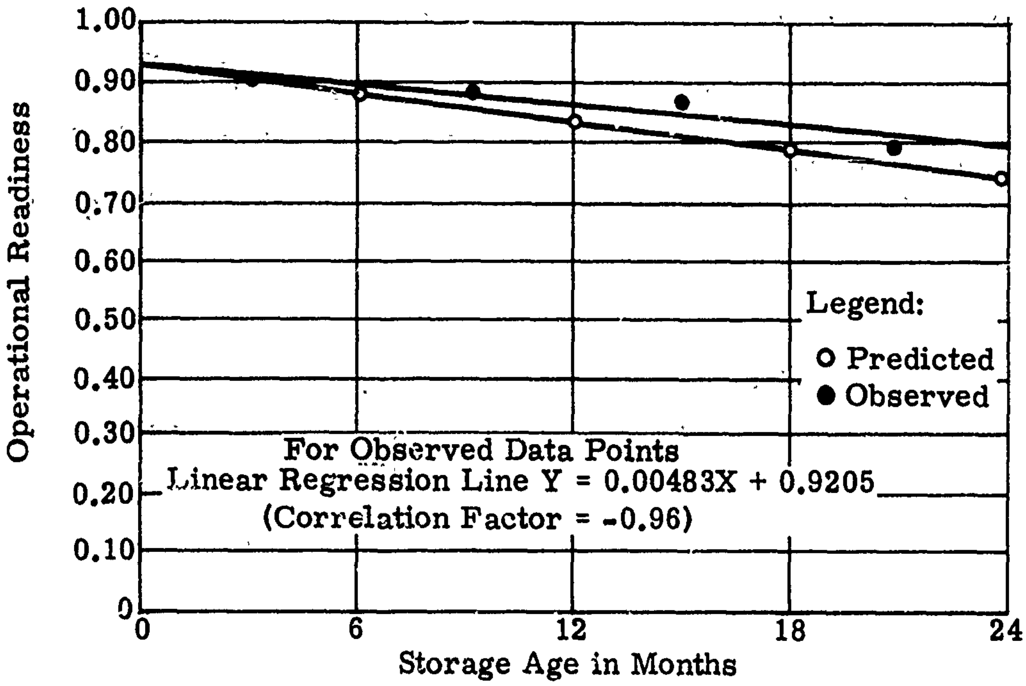



Figure 15. Surface-to-Air Missiles Storage Survival

## B. RECOMMENDATIONS

The following recommendations are submitted:

Government documents establishing and supporting reliability requirements such as the following should be upgraded to include provisions for nonoperating mode reliability requirements and predictions:

| | |
|---|---|
| MIL-STD-785(DoD) | "Reliability Program Requirements" |
| AFR 80-5 | "Reliability Program for Systems, Subsystems, and Equipments" |

Detailed Government specifications and procurement documents should also be revised and written to include assurance provisions that systems, subsystems, and equipments will be designed to survive extended nonoperating periods and maintain the required high reliability.

Reliability technology documents such as MIL-HDBK-217A, and RADC-TR-58-111, should be updated to reflect nonoperating failure rates, factors, and technology.

In light of the failure mechanisms uncovered during the nonoperating mode, the effects of transportation and handling on accelerating nonoperating failure rates merits further investigation. This is particularly important in view of current concepts proposing mobile systems.

On-off cycling failure data from dormant operating systems proved difficult to obtain. As a result, dormant data under very low operating stresses was collected since this information was most similar. Predictions for future on-off cycling dormant systems can be made by using this data together with acceleration factors based on the relationship between the degree of transient suppression and part derating which is specified.

The next step needed for major improvement of new systems is the determination of more cost effective techniques for screening parts to weed out hidden defects and the correlation of these screening methods with field reliability. In addition, the accurate quantification of the other reliability influence factors cited by this report will result in an upgrading of prediction methods.

## GLOSSARY

Age and Deterioration (A&D) Test - Test items in this program are functionally tested under ambient conditions for part deterioration due to aging. All items in this test group had previously been subjected to life tests.

Back-to-Back Testing - Through this method, items are tested twice in close succession, reducing the time between tests to as near zero as possible to determine the effects of turn-on transients and repeatability of test equipment and to segregate transient failures from storage-induced failures since the second (and subsequent) tests can yield only turn-on turn-off failure rates with $t = 0$.

Catastrophic Failure - A change in the characteristics of a part resulting in a complete lack of useful performance of the item.

Dormant Operating Mode - The state wherein a device is connected to a system in the normal operational configuration and experiences below normal or periodic electrical and environmental stresses for prolonged periods up to 5 years or more before being used in a mission.

Drift Failure - Any change in a measurement above or below the individual parameter range requirements stipulated in the part specification.

Evaluation Test - In this test, the items were subjected to a single stress and tested under assigned conditions for failure to meet the required specifications.

Fit - A failure per billion hours.

High Power Device - Rated at > 3 watts.

High Reliability Parts - See Part Class.

Microcircuit - A substrate to which a number of circuit elements are inseparably associated on or within a continuous body to perform the function of a circuit.

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Life Test - Items subjected to this type of test program are operated continuously for 23 hours per day, 6.5 days per week, which represents one cycle. Separation into groups allows three temperature ranges to exist during a cycle. This produces a minimum temperature group of -25°F, a maximum temperature group of +125°F, and a room ambient group of 77°F. The test duration is 4000 operation hours or until 10 failures occur in each of the 3 environments.

Low Power Device - Rated at < 0.3 watt.

Medium Power Device - Rated between 0.3 and 3.0 watts.

Military Standard Part - See Part Class.

Micromodule - An assembly of small discrete electronic parts in a high-density package.

Monolithic Microcircuit (CHIP) - A microcircuit with all components, including connections, manufactured on or into a tiny block of active substrate.

Multichip - A collection of two or more monolithic circuits housed in a single package.

Nonoperating Mode - Equipment in the storage and/or dormant operating mode.

Part Class

Commercial - A part which is not tested by the vendor and is not subjected to screening.

Military Standard - A part which receives Group A environmental tests plus Group B electrical tests per military specification.

Selected Military Standard - A serialized military standard part from selected vendors which receives burn-in plus 100 percent receiving inspection tests by the user.

High Reliability - A selected military standard part which is subjected to 100 percent burn-in and screens with an associated study program.

Part-Hour - The product of part quantity and nonoperating time.

Primary Nonoperating Failure - A failure that is correlated with an extended nonoperating time period.

Qualification Test - A program in which the test items are subjected to the following stresses before being functionally tested for failure to meet the required specifications:

1 High temperature

2 Low temperature

3 Temperature-shock

4 Shock

5 Vibration

6 Humidity.

Secondary Nonoperating Failure - A failure that occurs as a result of a Type A or B nonoperating failure on another part in the same circuit.

Substrate - The physical material upon which a circuit is fabricated.

Substrate, Active - A substrate for an integrated component in which parts of the substrate display transistance. Examples are single crystals of semiconductor materials.

Substrate, Passive - A substrate for an integrated component that may serve as physical support to a thin or thick film integrated circuit which exhibits no transistance. Examples are glass and ceramic.

Star Value - A fixed resistance selected by test.

Storage Mode - The state wherein a device is not connected to a system but is packaged for preservation and experiences somewhat benign environments.

Test-to-Failure - A test program that establishes the stress levels in temperature and vibration at which failure will occur.

Type A Nonoperating Failure - Failure that occurs as a result of physical or chemical processes which became evident after an extended non-operating time period.

Type B Nonoperating Failure - Failure that results from inherent manufacturing or design defects that pass initial functional tests but finally become evident after nonoperating time periods.

## APPENDIX A

## DATA COLLECTION

Data have been collected by Martin Marietta from testing operations described in Section 3. Other data collection consisted of a literature review and data source contacts at more than 80 defense contractors and government agencies.

### 1. Literature Review

#### a. Reliability Abstracts and Technical Reviews (RATR)

Thirty volumes of RATR (August 1964 to February 1967) were reviewed and pertinent publications obtained. Those documents containing the most valuable information on failure modes and mechanisms are included in the bibliography.

#### b. Interservice Data Exchange Program (IDEP)

A review of IDEP reports was continued throughout the duration of the contract. References 2 through 10 are those reports which were found to contain information on storage failure modes.

#### c. Reports Supplied by Rome Air Development Center (RADC)

Fifty-three reports supplied by RADC were reviewed for dormant operating or storage failure rate data, failure mechanisms encountered, and the environmental factors influencing the failure rates. Those individual reports containing the most significant data are listed in the bibliography.

#### d. Redstone Scientific Information Center (RSIC)

##### 1) RSIC Catalog Files

The closed document catalog files contained 18 documents with useful information. The publications were ordered from the Defense Documentation Center (DDC) and pertinent data extracted for inclusion in this report.

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2) RSIC Research Branch

A preliminary copy of a storage bibliography, prepared by the RSIC Research Branch for the Sergeant Project, was furnished to Martin Marietta. A review of this bibliography revealed 14 additional documents of interest. These publications were ordered from DDC and pertinent data included in this report.

3) DDC Bibliography on Long Term Storage Effects

At the request of Martin Marietta, the RSIC Library Branch had DDC search their records and prepare a dormancy and storage bibliography. This bibliography contains abstracts and titles on 198 documents. At the completion of the bibliography review, all appropriate documents were requested from DDC, reviewed, and the most significant documents are listed in the bibliography of this report.

4) NASA Bibliography

At the request of Martin Marietta, the RSIC Library Branch had the NASA document collection at Washington, D. C., searched. A bibliography of 2232 listings was obtained and appropriate documents were requested from DDC for inclusion of pertinent data in this report. This and all other master bibliographies have been retained and are available to qualified requestors.

e. Institute of Electrical and Electronic Engineers (IEEE)

All issues of the IEEE Transactions on Reliability from August 1963 to December 1966 and all proceedings of the Annual Symposium on Reliability from 1964 to 1967 were reviewed. Twenty papers were found containing varied information on dormant operating and storage technology. The most pertinent papers are listed in the bibliography of this report

f. Apollo Parts Information Center (APIC) and Parts Reliability Information Center (PRINCE)

A request was submitted to these NASA sponsored programs for dormant operating and storage information on diodes, microelectronics, and transistors. Data were received from APIC on microelectronics and transistors at various storage temperatures. These data were reviewed and, where applicable, used in combination with other data to establish temperature failure rate trends reported in Section IV.

2. Data Source Contacts

Through initial literature and telephone surveys, those government agencies, military installations, private research institutions, and electronic manufacturing firms having data pertinent to dormant operating and storage modes were contacted.

A summary of those data sources contributing to the dormant operating and storage study is shown in Table A-I. A discussion of each data source listed in Table A-I is contained in the following paragraphs.

TABLE A-I

Sources Having Data Available

| Source | Type of Data |
|---|---|
| Amelco, Mt. View, Calif. | High Temperature Storage, DCTL Microcircuits |
| Apollo Parts Information Center, Huntsville, Ala. | Temperature Storage on Semiconductors |
| Autonetics, Anahiem, Calif. | Minuteman I and II, High Reliability Parts, Dormant Operating and Storage |
| Battelle Memorial Inst., Columbus, Ohio | Microcircuit Reliability Report |
| Bendix, Ann Arbor, Mich. | Aerospace Industry Survey |
| Boeing, Seattle, Wash. | Minuteman Control System Tab Run |
| BSD, San Bernadino, Calif. | Minuteman II Data |
| Bell Telephone Laboratories, Whippany, N. J. | SPRINT and WS 107A MBGE Parts Data |
| Chrysler, Corp., Warren, Mich. | Jupiter Failures; Diode and Transistor Listings |
| CTS Corp., Elkhart, Ind. | Thin Film Information |
| Cubic Corp., San Diego, Calif. | Microcircuits |
| Douglas, Santa Monica, Calif. | Nike-Ajax Reports |
| Douglas, Charlotte, N. Car. | Nike-Hercules, Parts List |
| Fairchild Semiconductor, Mt. View, Calif. | Microcircuits Data |
| General Dynamics, Pomona, Calif. | Terrier and Tarter Failure Rates |
| General Electric, King of Prussia, Pa. | Selected Military Standard Parts Data |
| General Electric, Syracuse, N. Y. | Microcircuit Reliability Report |
| ITT Research Inst., Chicago, Ill. | Diode Life Tests |

TABLE A-I (Cont)

| Source | Type of Data |
| --- | --- |
| Intellux, Goleta, Calif. | Microcircuit Report |
| ITT, West Palm Beach, Fla. | High Temperature Storage on DTL Microcircuit |
| Lockheed, Sunnyvale, Calif. | Polaris Storage Data |
| Martin Marietta, Orlando, Fla. | Bullpup; Pershing, SPRINT Test Program |
| Martin Marietta, Baltimore, Md. | Gemini; Bunker-Ramo Computer |
| Martin Marietta, Denver, Colo. | Long Term Readiness and Environmental Program |
| Honeywell, Minneapolis, Minn. | Microcircuits |
| MIT Instrumentation Lab, Cambridge, Mass. | Microcircuit Reliability Report |
| Motorola, Pheonix, Ariz. | Microcircuits |
| Newark AFS, Newark, Ohio | Minuteman I Guidance System Part Failures |
| Ogden AMA, Ogden, Utah | Requested Minuteman Control System Part Failures |
| Philco, Lansdale, Pa. | Microcircuits |
| Philco, Santa Clara, Calif. | High Temperature Data on MECL and DTL Microcircuit |
| Planning Research Corp., Los Angeles, Calif. | Batteries, Motors, Explosive Devices |
| RADC, Rome, N. Y. | 53 Reports |
| Radiation, Palm Bay, Fla. | High Temperature Storage, DTL Microcircuit |
| Raytheon, Bedford, Mass. | Hawk Missile |
| Raytheon, Mt. View, Calif. | Microcircuits |
| RCA, Camden, N. J. | Ballistic Missile Early Warning System |
| Sandia, Alburquerque, N. M. | QA Evaluation System, Test and Stockpile Program |
| Scientific Data Systems, Los Angeles, Calif. | Microcircuits |
| Signetics, Sunnyvale, Calif. | Microcircuits |
| Sperry Utah, Salt Lake City, Utah | Sergeant Data |
| Sylvania, Mt. View, Calif. | Microcircuits |
| Texas Instruments, Dallas, Texas | High Temperature Storage Data, Microcircuits |
| Transitron, Wakefield, Mass. | Storage Life Test on Selected Military Standard Transistors |
| TRW Systems, Redondo Beach, Calif. | Microcircuit Data |
| Union Carbide Electronics, Mt. View, Calif. | Field Effect Transistors |

TABLE A-I (Cont)

| Source | Type of Data |
|---|---|
| U. S. Navy, Central Torpedo Office, Newport, R. I. | Shelf Life Evaluation of Parts |
| U. S. Navy, FARADA, Corona, Calif. | Microcircuit Data |
| U. S. Navy, FMSAEG, Corona, Calif. | Improved Tarter Evaluation Reports |
| U. S. Navy, Ship Systems Command, Washington, D. C. | PADLOC Project Data |
| Westinghouse, Baltimore, Md. | High Temperature on DTL IC's |
| Wright Patterson AFB, Dayton, Ohio | Microcircuit Storage Data |

a. Amelco

Amelco supplied a compilation of 2.1 million part-hours of high temperature storage data on DCTL microcircuits.

b. Autonetics

Minuteman I storage and dormant operating data prior to December 1964 and Minuteman II dormant operating data were received. These data are on high reliability parts and microcircuits.

c. Battelle Memorial Institute

The Electronic Component Reliability Center (ECRC) and the Advanced Electronic Section at Battelle Memorial Institute were contacted and the nonoperating information in each group reviewed.

The nonoperating data contained in ECRC is well organized; however, the quantity in part-hours is limited and is primarily from storage life tests run at elevated temperatures.

The Advanced Electronic Section has published a report (Reference 11) which contains operating failure rates, estimated nonoperating failure rates, acceleration factors for storage-life tests, and a summary of factors affecting microcircuits reliability.

In regard to storage data, the report states: "Several data points were available for storage life tests, so the Arrhenius theory was applied to investigate the possibility of true time acceleration. In all cases a constant hazard rate was assumed. The results indicated that such acceleration did occur". A detailed discussion of this phenomenon and the related failure rates and acceleration factors is presented in Section 4 of this report.

d. Bell Telephone Laboratories

A recent technical paper from Bell Telephone Laboratories (Reference 12) contained replacement rates on four different military systems and on undersea telephone cable links. The cable link data are on a special class of electronic parts and are used in Section 4E to determine relative nonoperating failure rates and factors for parts classes other than military standard parts.

In addition to these data, selected military standard parts storage information was obtained from the SPRINT missile guidance set and from the WS 107A missile borne guidance equipment used with the Thor Delta system.

e. Bendix Corporation, Bendix Systems Division

A copy of a survey (Reference 13) conducted among members of the Electronic Systems Reliability Committee of the Electronic Equipment Technical Committee of the Aerospace Industries Association was furnished by Bendix. The fifth question was of particular importance because it dealt with the use of a nonoperating failure rate. Only half of the respondents indicated the use of a nonoperating failure rate. Among those using the nonoperating failure rate, a failure rate of 0.1 times the normal base (operating) failure rate is most frequently used. The normal base failure rate used by the respondants, however, is not the same for each since some use MIL-HDBK-217, some RADC-TR-58-111, some values supplied by the Denver division of Martin Marietta, and others their own experience data to determine the normal base failure rate.

During this study, Martin Marietta has determined that a constant prediction factor applied to the operating mode cannot consistently be used to derive the nonoperating mode (see Section 6).

f. Boeing

The Boeing Company supplied a tab run on Minuteman control system failures from Wings 1 through 5.

g. Ballistic Systems Division, USAF

Dormant operating data on Minuteman Operational Ground Equipment (OGE) were obtained.

h. Chrysler Corporation, Missile Division

A compilation of Jupiter missile failure data and a list of potential storage data on 114 different diodes and 55 different transistors were provided. Recovery of the diode and transistor storage data from Jupiter field failure and quality records is too extensive and costly for the amount of data involved.

i. CTS Corporation, CTS Microelectronics Division

Over 300 million hours of thin film resistor data were received from CTS; however, the majority of the data was operating time, which are not pertinent to this study.

j. Cubic Corporation

About 1.1 billion part hours of storage data on microcircuits were obtained from 180 vote counters that Cubic Corporation produces. The microcircuits are equivalent to those used in military hardware because these devices are subjected to electrical and environmental tests in accordance with MIL-STD-750.

k. Douglas Aircraft Company, Missile and Space Systems Division

Two reports on the Nike-Ajax missile were provided, but a detailed parts list could not be furnished without a considerable expenditure of effort. The reports furnished are as follows.

1) Nike-Ajax Minimum Serviceable Life Determination (Reference 14)

This is a report on 16 Nike-Ajax missiles that had been in ready-storage throughout the United States from 10 to 30 months. The results of laboratory evaluation by Electromechanical Laboratories on an additional 16 missiles are included as pertinent.

2) Age and Usage Factors Affecting Missile Reliability (Reference 15)

The data contained in this report are based on 2500 Nike-Ajax firings. The major conclusions presented are:

1 Reliability is reduced by on-site ground use of the missile, e.g., training, unnecessary handling;

2 Overhaul performed on the missiles appears to eliminate the effect of age on firing reliability.

l. Douglas Aircraft Company, Charlotte Division

Circuit diagrams and a parts list of the Nike-Hercules were provided. Since no dormant operating or storage information is available on this missile, no further evaluation of this missile can be made.

m. Fairchild

Fairchild provided approximately 70 million part-hours of dormant information on RTL microcircuits and a report on radiation testing of linear microcircuits. About 1 million part-hours of accelerated temperature storage data on microcircuits were also received.

n. General Dynamics, Convair and Pomona Divisions

Storage and stowage data on the Improved Terrier and Homing Tarter missiles were received. This information is to part level and includes electronic items such as resistors, capacitors, transistors, diodes, transformers, relays, and instruments. These data are contained in the failure rates listed in Section 4.

In addition to the above data, the Convair Division has recently prepared a report of a study on dormant missile systems (References 16 through 18).

o. General Electric, King of Prussia, Pennsylvania

Data on a total of 7,390,000 part-hours of semiconductor storage on selected military standard parts were received. These data were acquired from 3 years of storage on parts from the Advent Program.

p. General Electric, Syracuse, New York

WPAFB supplied an interim GE progress report entitled "Techniques for the Control of Integrated Circuits Quality and Reliability." This work is being performed under Contract AF 33(615)-2716, and final results are not available at this time.

q. IIT Research Institute (Formerly Armour Research Foundation)

Operating life test data on 1N538 and 1N540 silicon metallic rectifiers were obtained from two separate reports (References 20 and 21). These reports indicate a definite difference in long term performance of identical rectifiers built by different manufacturers and that "careful consideration should be given to the selection of a manufacturer in terms of a particular application."

r. Intellux

A report was received on microcircuits. This report contains information useful for preparing design notes, but very little storage data are included.

s. International Telephone and Telegraph

ITT supplied high temperature storage data on DTL microcircuits, amounting to 662,000 hours.

t. Lockheed Missiles and Space Company

The Lockheed Missiles and Space Company reviewed the Polaris missile program for data on nonoperating modes.

Lockheed contributed a limited amount of data on microcircuits which, while under no load, were exposed to various levels of nuclear radiation. These data are not of sufficient quantity to be meaningful in a nonoperating failure rate determination for nuclear exposure. The Navy Special Projects Office was queried for storage data from that portion of the Polaris A3P system where failures are isolated to the part level. About 9 billion part-hours of data were obtained.

u. Martin Marietta Corporation, Orlando Division

Data from Martin Marietta report OR 3482, "Reliability Assessment of Stockpiled GAM-83A Nose Sections" were obtained (Reference 22). This report contains the results of a test program conducted to establish reliability degradation in the Bullpup nose sections as a result of storage. A sample of 21 nose sections between 2 and 3 years of age was included in this test program. Evidence of storage degradation was noted in two major assemblies.

Storage data from the SPRINT control system were compiled for selected military standard electronic parts.

Data from OR 6596, "Pershing Storage Reliability Report," (Reference 23) were obtained from the results of after-storage tests conducted at Pueblo Depot on 230 guidance and control sections, 169 first-stage sections, and 155 second-stage sections. Storage times ranged from 1 to 24 months, from the time of factory acceptance test until the first test at the Pueblo Depot. The most significant conclusion in this report is that the storage failures conform to a Poisson process since the failure rates were observed to be constant with time. Therefore, the exponential distribution

may be used to calculate the probability of surviving the storage mode for this weapon under the observed environments.

Data from the Pershing Product Evaluation were also obtained. The objective of this program is to provide verifying evidence of production quality and to detect degradation of product quality and reliability. Samples are selected at random from the production stockpile and are tested at specific intervals to determine trends. Items under test include control computers, main distributors, firing unit assemblies. inverters. and cable assemblies. A summary of this program is contained in OR 6591 (Reference 24).

As part of the environment test program for the Pershing Weapon System, a 5-year age and deterioration program was initiated in August 1961 to determine the effects of aging on Pershing missile system performance. Pershing missile 307 was designated for the program. This program concluded with the semiannual systems test which was performed in August 1966.

Pershing missile 307 includes approximately 20 major components. These major components are made up of approximately 2400 electrical, electronic, electromechanical, and mechanical parts (excluding structural parts). During a 5 year period, these items have been subjected to cyclic temperature and humidity stresses in a semitropical environment with handling, transportation, and operational stresses experienced semiannually. The test results of missile 307 are reported in a series of OR 1990 reports (Reference 25).

Data on 493 BIRDiE flip/flop cards, which had been stored for 28 months in the Tobyhanna Army Depot, were also taken from a Martin Marietta Company memorandum (Reference 26).

The failure rates associated with the above data have been determined to the part subclass level and are reflected in the failure rates shown in Section 4.

In addition to the above data, Martin Marietta will be conducting age and deterioration tests on the SPRINT missile system. This test is currently in the planning stage and results will not be available for a few years.

v. Martin Marietta Corporation, Baltimore Division

Data from the Gemini program have not been recorded in a manner that enables recovery of significant amounts of nonoperating data. Storage data may exist at the Bunker-Ramo Corporation on a computer design that utilizes commercial parts. No further effort was expanded to collect this information because of the low priority established for data on commercial parts.

w. Martin Marietta Corporation, Denver Division

The Denver Division is currently conducting a long term readiness and environmental test program for the Air Force on Titan II missiles. The program consists of checking out seven missiles that have been in a dormant operating condition for periods up to 3 years. Complete data from this program are not available at this time.

x. Honeywell

Eighty-eight thousand hours of storage data on Texas Instruments microcircuits SNR 923 and SNR 924 were received. These data were taken at high temperatures, and no failures were experienced.

y. MIT Instrumentation Lab

A report entitled "The Application of Failure Analysis in Procuring and Screening of Integrated Circuits" which was prepared by MIT was received for evaluation (Reference 55).

z. Motorola

Both dormant operating and storage data were received on Motorola microcircuits. Fifty-two million part-hours of dormant operating and 5 million part-hours of storage data were obtained. These data were acquired from the Motorola reliability report on Monolithic, Digital Integrated Circuits, and represent both ambient and high temperature testing (Reference 50).

aa. Newark Air Force Station

A tab run on failed electronic parts from the Minuteman guidance system was provided by Newark. This information was used together with operational part hour data from SAC Headquarters to obtain Minuteman I failure rates from December 1964 to the present.

bb. Philco, Lansdale, Pennsylvania

A reliability report (Reference 49) on planar epitaxial microcircuits was provided. The data were almost entirely at elevated temperatures.

cc. Philco, Santa Clara, California

Reports on 1.2 million part-hours have been received from Philco relating to high temperature tests on MECL, DTL, and RTC microcircuits

dd. Planning Research Corporation

A Planning Research Corporation Report (PRC R-377) (Reference 27) was received and reviewed. Data applicable to electronic and electro-mechanical parts were extracted and included in the calculation of non-operating failure rates.

ee. Radiation, Inc.

Data from 1.1 million part-hours of high temperature storage of DTL microcircuits has been received from Radiation.

ff. U. S. Air Force, Rome Air Development Center (RADC)

A conference, jointly sponsored by the U. S. Army and the U. S. Air Force, was held at RADC on the reliability aspects of dormancy and storage. References 30 and 32 through 37 were presented at this conference, and information from these papers was used in preparing this report.

In conjunction with the fourth annual symposium on the physics of failure in electronics which was sponsored by RADC, a Martin Marietta report was prepared (Reference 38). This report represents a review of the literature covering the period from October 1961 to November 1965.

gg. Raytheon Company, Missile Systems Division

A recently published Raytheon report on the Hawk Missile (Reference 30) contains an excellent table of storage failure rate information. This information is based on a group of 973 Hawk missile stored at Red River Arsenal for periods varying from 1 to 8 months.

hh. Radio Corporation of America, Defense Electronics Division

BMEWS program, AGREE report, and Naval Shipyards Materials Laboratory data were received in a technical paper from RCA (Reference 28).

Most of these data are on tests at extreme conditions or they are not quantitatively defined; hence, these data are most useful as environmental indicators rather than for calculating failure rates.

RCA at Moorestown, New Jersey is preparing to test a radar system containing approximately 2000 microcircuits that has been in storage for over 2 years.

ii. Sandia Corporation

Data from Sandia's quality evaluation system test program and the stockpile sampling program were obtained. These programs were initiated by Sandia to maintain a constant surveillance on the stockpile of all items for which Sandia is cognizant.

All parts used by Sandia are manufactured in accordance with Sandia specifications, which are more stringent than military standard specifications. Failure rate data on the Sandia parts are reflected in the failure rates shown in Section 4.

jj. Scientific Data Systems

Scientific Data Systems produces a Sigma 7 computer containing over 10,000 microcircuits. They have agreed to review their records and provide any storage information they have, including a list of the types of microcircuits used in their computer. This information, however, will not be received in time to be included in this report.

kk. Signetics

Over 6 million part-hours of accelerated temperature storage data on microcircuits were received in a Signetics report of their reliability testing program.

ll. Sperry Utah Company

Data on 64 Sergeant missiles, including the length of time in storage, the number of failures, the failure analysis, and a generation breakdown were received from the Sperry Utah Company. Each missile was tested prior to and after storage periods at the Sperry Clearfield Facility.

mm. Sylvania

About 235 million part-hours of microelectronics data were received from Sylvania.

nn. Texas Instruments

About 5 million part-hours of accelerated temperature storage data on microcircuits were received from Texas Instruments.

oo. Transitron

Reports were received on testing of high reliability-type transistors.

pp. TRW Systems

Approximately 172 million part-hours of storage and dormant operating data were received, representing six microcircuit manufacturers.

qq. Union Carbide

Approximately 2.8 million part-hours of dormant operating and 1.2 million part-hours of storage data were received on field effect transistors.

rr. U. S. Navy Central Torpedo Office

Seventeen reports were received on shelf life evaluation of various torpedo parts. Typical shelf life test duration was 5 years, but some parts were in storage for as long as 7 years.

ss. U. S. Navy Farada

From the FARADA Files, approximately 39 million part-hours of integrated circuit storage data were received. The data represent microcircuits used in equipment manufactured by AC Spark Plug. Additional information was supplied by AC Spark Plug. Dormant operating part-hours totaling 3.7 million and 40.2 billion storage part-hour data were obtained for high reliability-type semiconductors used in equipment manufactured by IBM.

tt. U. S. Navy Fleet Missile System Analysis and Evaluation Group

This military installation, through the Bureau of Naval Weapons, has made available information on the Technical Evaluation Project for Improved Tarter missiles (BUWEPS SMS Test 1-64) (Reference 41).

A total of 150 Improved Tarter missiles were used in this test and were stowed aboard ship for periods ranging from 4 to 11 months.

Stowage (storage) failure rates for these missiles were calculated only to the part level, because a description to the subclass level was not available. This information is reflected in Section 4.

uu. U. S. Navy Ship Systems Command

About 21.2 million part-hours of dormant operating data on microcircuits were obtained from the PADLOC Project.

vv. Westinghouse

Data on 342,000 part-hours of high temperature storage on DTL microcircuits were received from Westinghouse.

ww. U. S. Air Force, Wright-Patterson AFB

A working paper entitled "A New Concept of Planned Inspections" (Reference 39) was received from Wright-Patterson AFB. This report does not contain any dormant operating or storage data. It does present a theory, Predict and Preclude, which utilizes warnings given in the form of specific parametric changes in various items prior to failure. Knowledge of these parametric changes will enable the determination of optimum inspection intervals for military equipment.

Information on a GE contract (AF33-615-2716) to study microcircuit reliability was also received from WPAFB.

In addition to those companies and government agencies referenced as data sources, many other sources were contacted but it was found that their data were neither suitable for this study nor readily retrievable from storage. These sources are listed in Table A-II.

TABLE A-II

Sources Not Having Data Currently Available

Alpha Microelectronics Inc., Beltsville, Maryland
Amperex Electronics Inc., Slatersville, R. I.
Atlantic Instruments and Electronic Inc., Newton, Mass.
AVCO, Wilmington, Mass.
Avionics Lab, Wright Patterson AFB, Ohio

TABLE A-II (Cont)

Bunker Ramo, Canoga Park, Calif.
Bunker Ramo (Teleregister), Stamford, Conn.
Burroughs, Paoli, Pa.
Centra Lab, Milwaukee, Wis.
Collins Radio, Cedar Rapids, Iowa
Douglas Aircraft, Culver City, Calif.
U. S. Army Elect. Command, Ft. Monmouth, N. J.
General Instruments, Hicksville, L. I., N. Y.
General Microelectronics Inc., Santa Clara, Calif.
Goddard Space Flight Center. Greenbelt, Md.
Hughes Aircraft, Culver City, Calif.
Monitor Systems, Ft. Washington, Pa.
National Semiconductor, Danbury, Conn.
Norden, Norwalk, Conn.
North Electric, Gallion, Ohio
Power Components Inc., Scottdale, Pa.
Sanders Associates, Nashua, New Hampshire
Siliconix, Sunnyvale, Calif.
Sprague, North Adams, Mass.
Sperry Rand, St. Paul, Minn.
Sterling, Walter, Inc., Clarmont, Calif.
Stewart Warner, Santa Clara, Calif.
Sylvania, Williamsville, N. Y.
Sylvania, Woburn, Mass.

# APPENDIX B

## FAILURE ANALYSIS

The physics of the failure approach, i.e., the search for basic failure modes and mechanisms, has been performed systematically on all electronic hardware that failed during the Martin test program. This test program is described in Section 3.

The first step in these investigations was to determine whether the occurrence of failures was correlated with testing or the nonoperating time. Only the failures correlated with nonoperating time are considered in this report.

The second step consisted of evaluating the failures to categorize them into two basic causes:

Type A - Failures caused by chemical and physical reactions that became evident after an extended nonoperating period;

Type B - Inherent manufacturing or design defects that passed initial functional tests and finally became evident after nonoperating periods.

The actual laboratory failure analysis was conducted according to the following procedure:

1 Extensive electrical tests of the characteristic parameters of the particular part to verify and pinpoint the exact nature of the failure mode;

2 X-ray analysis of the specimen prior to dissection;

3 Gross and fine leak tests to check hermaticity, if applicable;

4 Dissection and microscopic examination (up to 2000X) for visible failure mechanisms;

5 Additional analyses as required -

a Chemical analysis

b Metallurgical analysis

c Cross-sectioning of semiconductor junctions

d Electron probe analyses in diffusion and crystal studies;

6 Photographing the characteristic evidence of failure mechanisms.

Detailed reports of these analyses are found in Subsection 1 of this Appendix.

1. Case Histories

a. Type 1N315 Diode

1) Component Construction

This glass case germanium diode type failed twice. Its construction is shown in Figure B-1.

2) Determination of Failure Modes and Mechanisms

One diode was found to be shorted during electrical tests. Microscopic examination failed to reveal any defect in the wire whisker or the germanium chip; however, examination revealed numerous cracks in the glass case around the lead-in wires. This is a common condition in glass-encased diodes which can lead to the introduction of moisture into the diode case. The check, to determine whether moisture is the cause of a short, was made by applying heat to drive off any moisture present and then repeating the electrical measurements. There was an increase in resistance with an increase in temperature, indicating that moisture was present.

This failure is Type A because the cracks were formed and increased in size over a period of time due to temperature change and a difference in the expansion coefficients of the glass case and lead-in wire.

b. Type 1N1735 Silicon Diode

1) Component Construction

The 1N1735 diode is contained in an epoxy-coated metal case as shown in Figure B-2. This type suffered two failures.

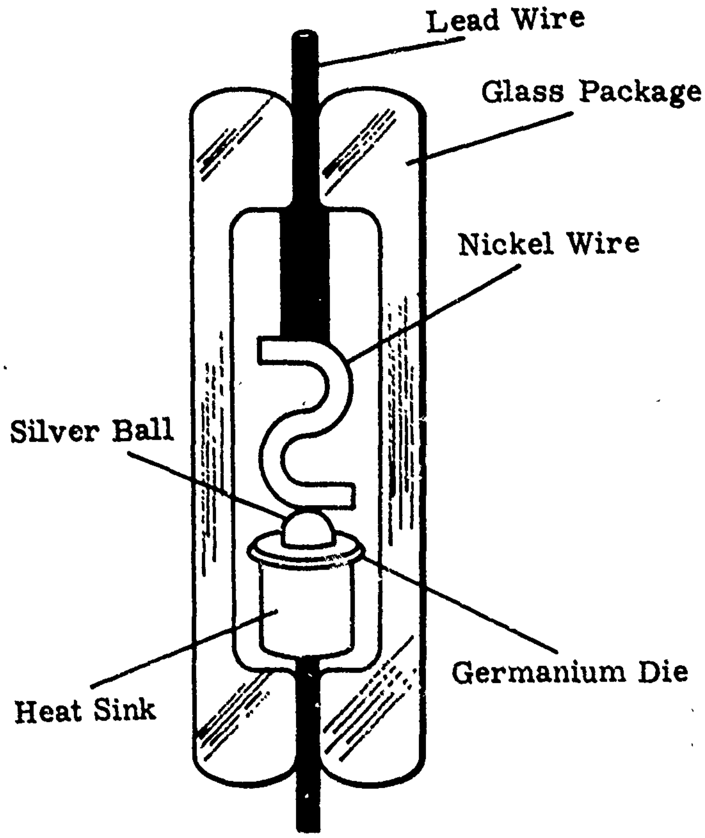


Figure B-1. Diode (1N315) Construction

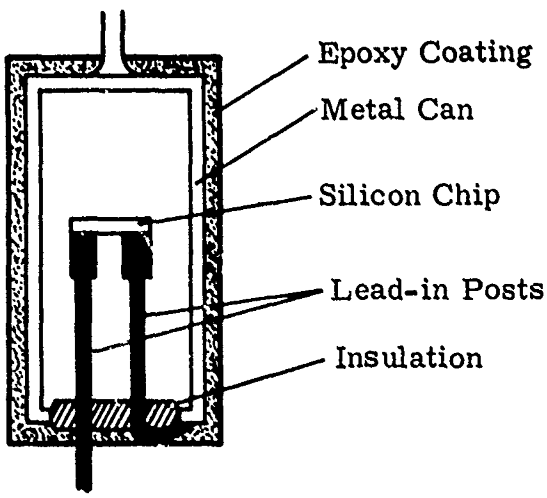


Figure B-2. Diode (1N1735) Construction

2) Determination of Failure Modes and Mechanisms

a) Short

One silicon diode exhibited a short during electrical tests. X-ray examination failed to reveal any obvious defect. The epoxy coating was carefully chipped from the metal can and the mechanism of the short became exposed as shown in Figure B-3.

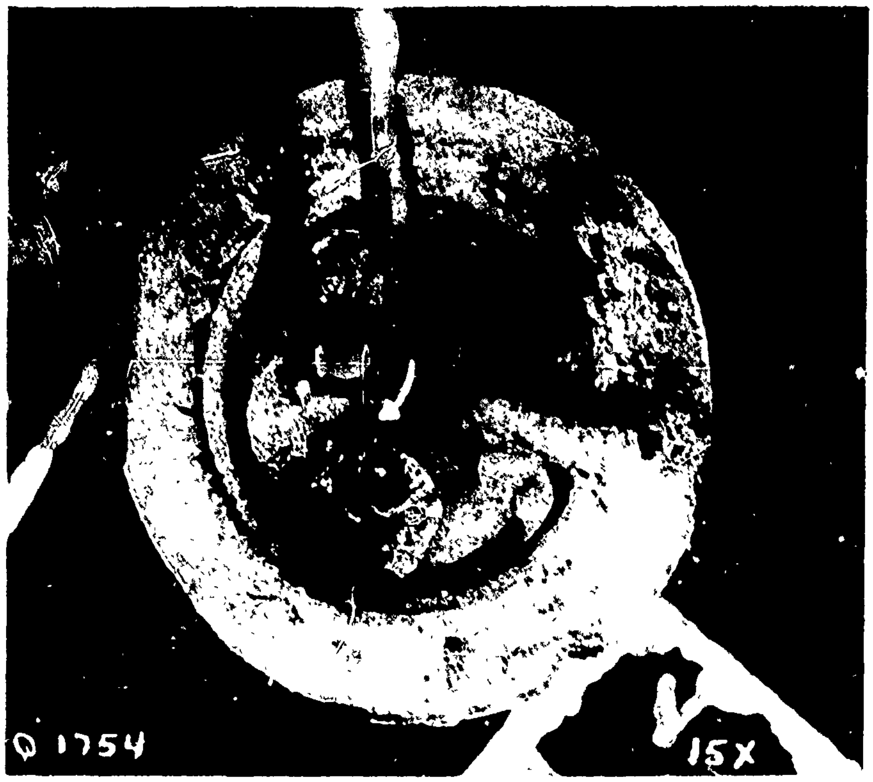


Figure B-3. Shorted 1N1735 Diode

It was evident that an excess of solder had been deposited on the insulation outside of the metal case and then covered by the epoxy. The solder is making contact just enough to cause a short. To verify that the solder was the cause of the short, the silicon chip was removed and the short was found to still exist. Evidently, the short was not completely made when the part was manufactured; instead, expansion and movement of the leads completed the circuit. This is a Type B failure, caused by an inherent manufacturing defect that became evident after storage and testing.

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b) Open

Electrical analysis showed one open failure for this part. X-ray analysis showed no defect; however, removal of the epoxy and dissection of the can exposed a loose silicon chip. The bond between the chip and lead-in posts was not strong enough and the chip came off with age and handling. This appears to be a Type B failure.

c. Wet Electrolytic Tantalum Capacitor

1) Part Diagram

The wet electrolytic tantalum capacitor (2.5 mfd, 70 Vdc) is constructed as shown in Figure B-4. Two failures were observed for this type.

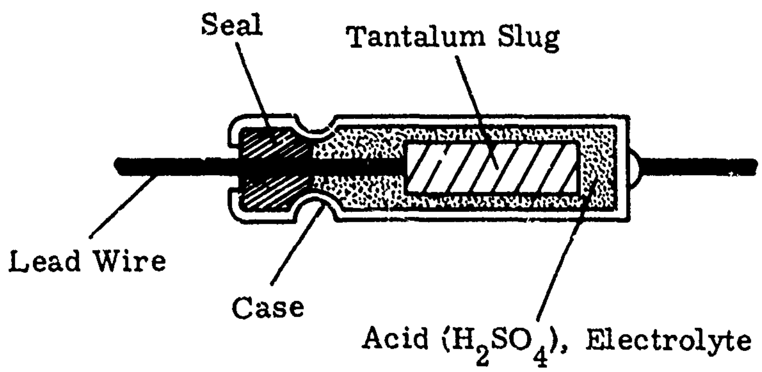


Figure B-4. Capacitor, Tantalum, Wet Electrolyte, Construction

2) Determination of Failure Modes and Mechanisms

During electrical tests, two tantalum capacitors exhibited very high leakage currents. The capacitors were removed from the circuit and subjected to X-ray examination. The X-ray photos showed a deposit of material connecting the anodes (tantalum slugs) to the capacitor cases. The cases were opened and inspection revealed sufficient deposits on the anode slug to partially short it to the case.

To explain this phenomenon, it must be shown that the common failure mechanism for capacitors of this type is leakage of the seals. It is not unusual for this to result in partial or complete loss of the electrolyte or the introduction of impurities and moisture into the case. Subsequent

chemical analysis of the deposit on the slug and case showed it to be silver sulfide (Figure B-5 and B-6). These two failures can be classified as Type A because of the chemical reaction of the acid electrolyte with the silver case over an extended period in storage.

The latest designs of this type of capacitor incorporate a perforated teflon liner on the inner wall of the case to aid in preventing shorts from slug to case.

d. Solid Tantalum Capacitor

1) Primary Failure - Capacitor

A tantalum capacitor (6.8 mfd, 35 Vdc) exhibited very high current leakage during electrical tests. X-ray photographs of the part failed to show anything conclusive. After the part was opened, analysis of the manganese dioxide type paste disclosed that extra moisture was present. A fine coating of condensed water vapor was observed on the inside surface of the eyelet and seal. It is probable that the failure mechanism in this instance was a leaky seal which allowed moisture to form a current path from lead to case. This failure can be classified as Type B.

2) Secondary Failures

Two Type 2N1132PNP transistors in the circuit with the capacitors exhibited shorts in the form of burned-out emitter leads. This was detected by X-ray and microscopic examination. These failures can be attributed to the excessive current in the emitter circuits caused by the cap citor shorts. Therefore they are classified as secondary failures.

e. Type MM-999 Transistor, PNP Mesa Chip

Electrical analysis of the part showed an opening in the transistor from the collector to the emitter and from the emitter to the base. When examined microscopically, the emitter lead was found to be broken off where it had been attached to the mesa transistor chip. The lead wires in this type of transistor are wedge or pressure bonded to the transistor chip. It was apparent from the examination that too much pressure had been used in making the pressure weld, leaving the lead wire too thin at the point of contact with the chip. During storage and handling, the lead wire finally shifted to the open position. This failure is Type B, where the manufacturing defect did not become apparent until after storage.

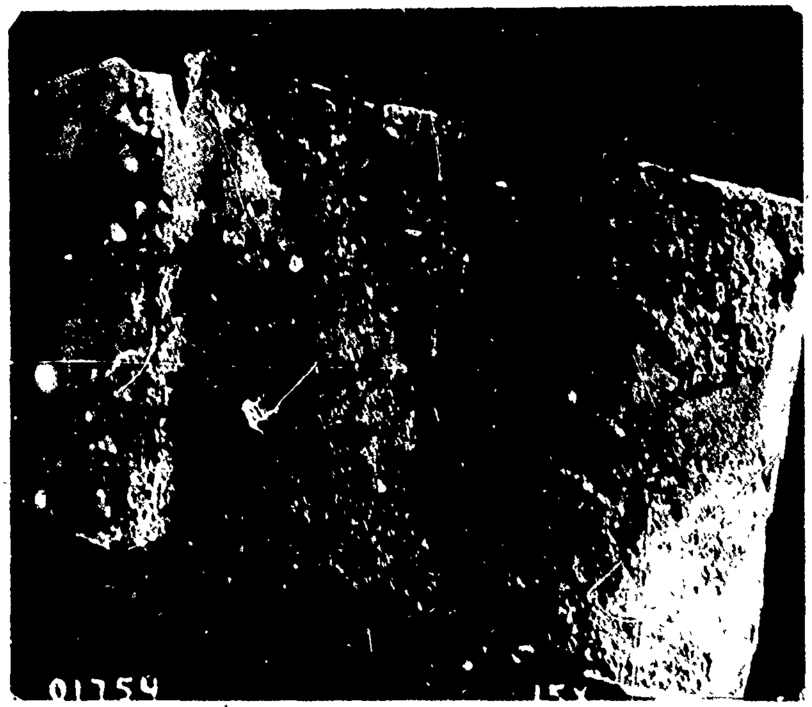

Figure B-5. Corroded Case - Wet Tantalum Capacitor

Figure B-6. Deposit on Slug of Wet Tantalum Capacitor

f. Type 2N2857 Transistor, NPN

1) Part Junction Construction

Figure B-7 shows the details of the 2N2857 transistor junction. Three failures on this part type were noted.

2) Determination of Failure Modes and Mechanisms

Electrical analysis of these parts indicated emitter to base shorts. After the cases were opened, microscopic examination revealed a metalization path across the extremely close tolerance clearances between the emitter and base fingers as shown in Figure B-7. It was observed from the excess metalization that the failures resulted from improper deposition of the contract material. The excess emitter contact metalization was almost, but not quite, touching the base metalization, and this allowed the parts to pass initial screening tests. Differential thermal expansion during storage caused contact to be made and when operating current was applied during test the short became evident. This is a Type B failure.

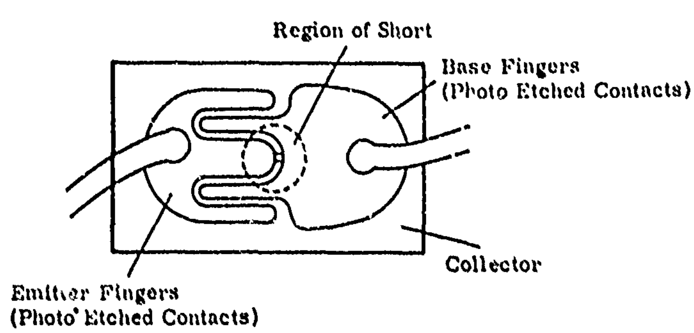


Figure B-7. Transistor Junction Construction

g. Wet Electrolytic Tantalum Capacitor

1) Part Diagram

The construction diagram for this tantalum capacitor is shown in Figure B-8.

2) Determination of Failure Modes and Mechanisms

Primary analysis indicated that the capacitor was shorted directly. The part was then dissected for further analysis (Figures B-8, B-9, and B-10). It was evident from visual inspection that a hole or scratch in the inner coating, which is acid resistant, permitted the acid electrolyte to etch a hole in the inner silver case (Figure B-9). The acid electrolyte was then in contact with the outer aluminum case (Figure B-11). It, of course, then reacted with the aluminum case and steel anode to form metallic salts (mostly $Al_2SO_4$ with FeS as determined by qualitative analysis spot tests) which were deposited (Figure B-10) between the inner and outer capsule cases, causing the direct short (Figure B-8). This can be considered either a Type A or a Type B failure, depending on whether the etched hole was made by a scratch on the inner coating, and missed by manufacturing inspection or, over a long period, the acid finally ate through the coating at the region of least thickness.

h. Type 2N335 NPN Silicon Grown Junction Transistor

1) Junction Structure - Silicon

The construction of the junction of the 2N335 transistor is shown in Figure B-12.

2) Determination of Failure Modes and Mechanisms

Electrical analysis showed identical failure modes for two of these transistors. Both had a collector-to-emitter and a collector-to-base open junction.

After the cans were opened it was evident with microscopic inspection that the silicon chip had broken in the collector region in both cases (Figure B-12). It seems probable that a fault or crack had occurred in the chip at the time the chip was bonded to the collector and emitter posts. After a period of storage and handling, the chips finally became completely separate at the site of the faults. These are Type B failures.

In the latest designs of this transistor, the silicon chip has been repackaged to provide uniform support over its entire length by laying it directly on a teflon insert which is firmly supported by the header.

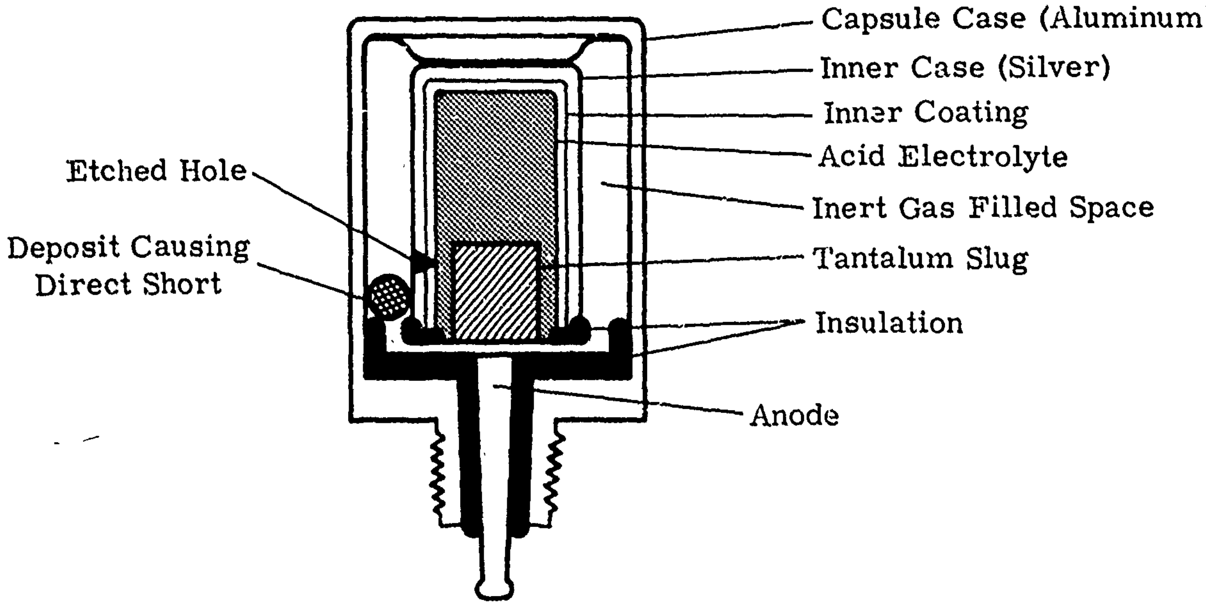


Figure B-8. Capacitor, Wet Tantalum, Construction

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Figure B-9. Etched Hole in Internal Case - Wet Tantalum Capacitor

Figure B-10. Deposit Causing Direct Short - Wet Tantalum Capacitor

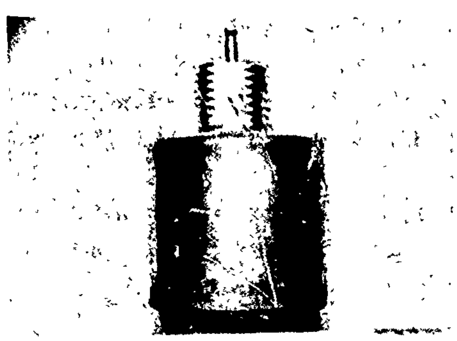

Figure B-11. External Aluminum Case - Wet Tantalum Capacitor

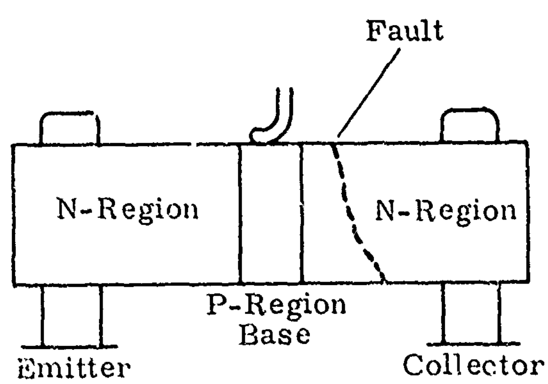


Figure B-12. Transistor (2N335) Junction Construction and Fault

i. Metal Film Resistor, (700Ω) and (576Ω)

1) Part Diagram

The internal construction of these metal film resistors, of which two failed, is shown in Figure B-13.

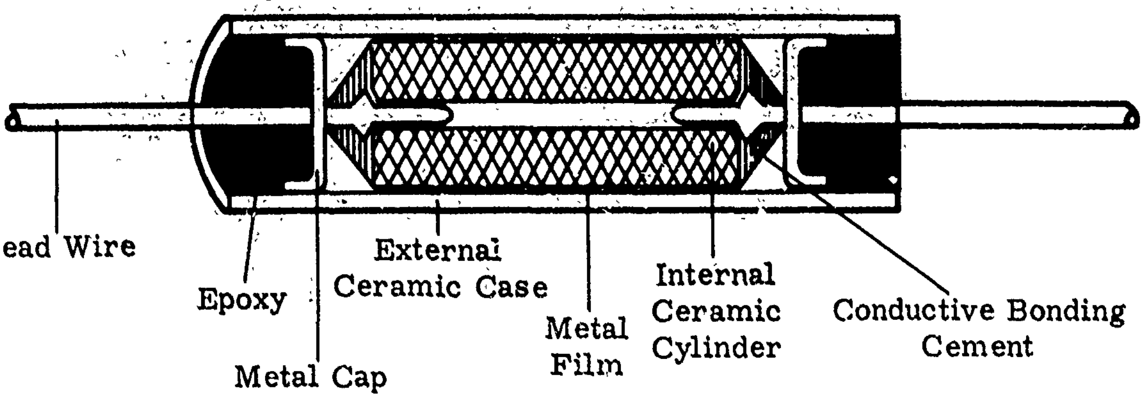


Figure B-13. Resistor, Metal Film, Construction, Specimens A and B

2) Determination of Failure Modes and Mechanisms

Measurement of these two resistors on a bridge indicated that the resistance was outside the percent tolerance limits. To check for the characteristic failure mechanisms of this part, namely, poor contact of the bonding cement, pressure was applied inwardly to both leads of the resistors. With an increase in pressure, the resistance was reduced in both cases to the rated values. This indicated a loosening of the conductive bonding cement, therefore the parts were taken apart to verify this. Figures B-14, B-15, B-16 show that the cement had indeed dried and separated from the film-covered internal core. Figures B-14 and B-15 are of specimen A and Figure B-16 of specimen B.

These two resistor drift failures are then classified as Type A, since the conductive cement, which is supposed to be permanently elastic in quality, has dried out over a period of time.

j. Metal Film Resistor, 700 ohms

1) Part Diagram

Figure B-17 details the internal construction of the 700 ohm resistor, one of which failed.

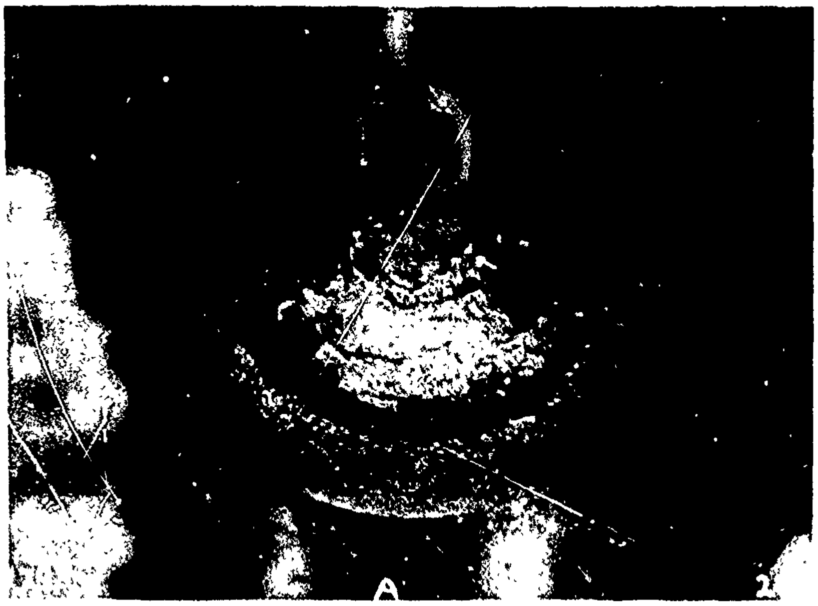

Figure B-14. Bonding Cement Separation (Top View), Metal Film Resistor, Specimen A

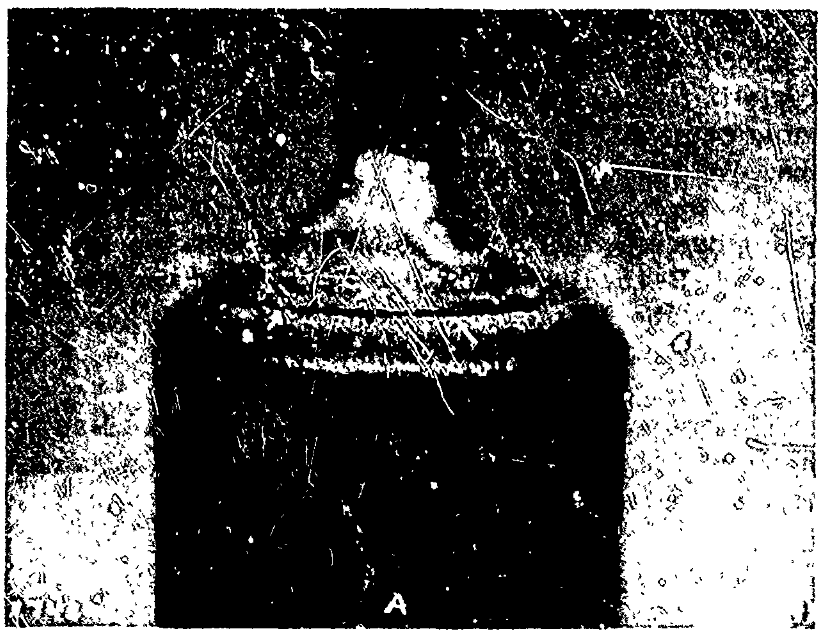

Figure B-15. Bonding Cement Separation (Side View), Metal Film Resistor, Specimen A

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Figure B-16. Bonding Separation, Metal Film Resistor, Specimen B

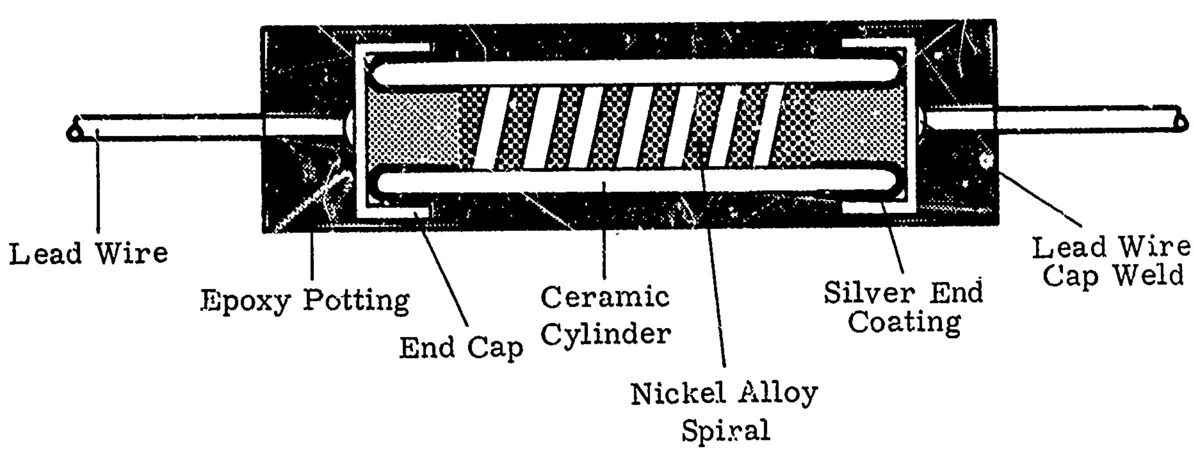


Figure B-17. Resistor, Metal Film, Construction, Specimen C

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2) Determination of Failure Modes and Mechanisms

Resistance bridge measurement of this resistor indicated a resistance of approximately 700 kilohms, in contrast to the rated 700 ohms. This indicated that there was an almost complete open in the resistor, located in either the weld of the lead wire-to-cap, the junction of the end cap-to-coated end of the ceramic cylinder, or the nickel alloy spiral itself. To find the failure mechanisms, the epoxy was chipped away from the resistor and the end caps removed. The lead wire welds were tested and found to be good. A resistance reading across the spiral indicated that the failure mechanism was in the spiral itself. The spiraled metal film cylinder was sliced lengthwise with a 5/1000 cm diamond saw. Microscopic examination revealed a flaking of the spiraled film (Figure B-18). The flake in the film had almost completely opened the circuit.


Figure B-18. Flaking of Metal Film Spiral - Metal Film Resistor, Specimen C

Further examination revealed the presence of minute particles under the metallic film. These particles were evidently the cause of the flaking of the spiral as temperature fluctuations were experienced by the resistor. The expansion coefficients for the nickel alloy film and the ceramic substrate were of sufficiently different values to cause the flaking of the film where the particles were coated over. This is a Type A failure.

k. Electronic Gate Microcircuit - Intermittent Short

This shorted electronic gate was responsible for the failure of its next assembly, a micromodule circuit. When the part was opened and examined microscopically, the cause of the intermittent short was immediately evident (Figure B-19). This intermittent short was caused by loose metallization in the container. It can be seen from the photograph that the metal came from the contact area where the lead wire had been improperly bonded. This is a Type B failure.

Figure B-19. Bonding Procedure Error - Microcircuit

1. Electronic Gate Microcircuit - Direct Short

Electrical analysis of the microcircuit indicated a direct short between the input diode and ground pin. Originally, this item had been a component part of a micromodule circuit. The failure of the module was pinpointed to the electronic gate.

After the failure mode was determined, the microcircuit container was opened to determine the failure mechanism. Microscopic inspection revealed the short on the microcircuit chip. There was a bridge of material between the diode and ground contacts (Figure B-20). The black dot in the upper center of Figure B-20 is a particle of coating from the can introduced during opening.

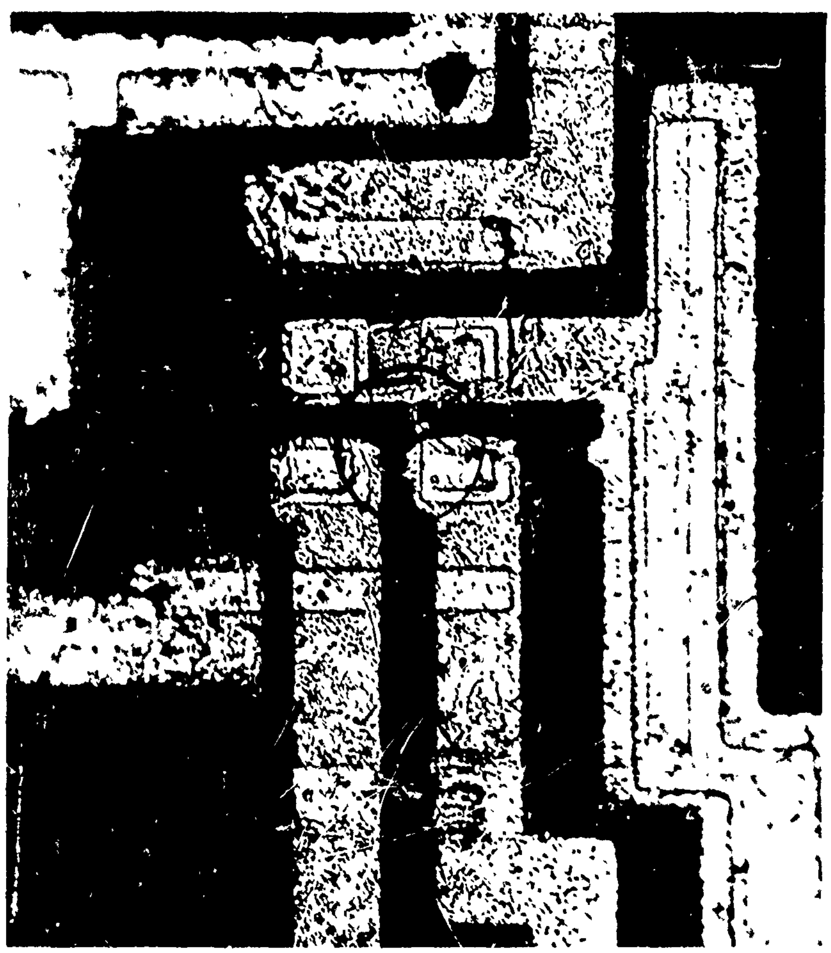

Figure B-20. Improperly Etched Contact Material - Microcircuit

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Further inspection of the die surface revealed the origin of the failure to be contamination in the form of loose particles of deposited aluminum conductor. Apparently the material was left on the die during the etching process and was not removed by washing prior to hermetic sealing. The free particles were later able to accumulate at a position on the circuit (see circle, Figure B-20) which formed a shorting bridge. This is classified as a Type B failure.

m. Electronic Gate Micromodule

This micromodule, which failed once, was subjected to electrical tests, and the failure mode was determined to be a disappearance of output signal or a variance in the signal level. These intermittent phenomena could be made to occur by exerting horizontal pressure on the module while it was mounted in the test console socket. This was done by gently tapping the module while maintaining the output signal. Further analysis revealed that one pin (No. 13) had an intermittent open weld connection inside the module potting. The mechanism of this failure was concluded to be a faulty weld connection on pin No. 13.

This was a Type B failure, i.e., it was caused by an inherent manufacturing defect that remained concealed until a period of nonoperating time had elapsed.

n. Input Converter Micromodule

Upon electrically testing this input converter module, which failed once, it was found that one of its four circuits was defective. The failure was pinpointed to be across a diode (T1257) and a 3650 ohm resistor. The reading across these two circuit elements was 50 kilohms, whereas the (normal) reading in the other three circuits was between 10 and 11 kilohms. The high resistance reading was determined to be caused by the T1257 diode. When the module was depotted to expose the diode, the glass body of the diode was found to possess multiple cracks. Applied pressure on the leads would change the ohmic value of the diode. It was thus concluded that the failure mode of high resistance was the result of a poor internal diode circuit contact. The mechanism of this failure apparently was the shrinkage of the potting material which cracked the diode glass and damaged the diode internally. Further substantiation of this mechanism was furnished when it was found that two microcircuit cans had been subjected to the effects of high pressure as evidenced by a concave shape on the tops of the cans. The failure of the diode was Type A.

o. Microcircuit, Dual Line Driver

Test history on this device shows a definite trend of increasing reverse leakage current of the diode located at input pin No. 9. Further tests showed breakdown beginning at $2V_R$ as compared to $6.5\ V_R$ of the other diodes similarily located at the remaining seven inputs. A gross leak check conducted per MIL-STD-202C method 112 revealed leakage appearing to originate from the lead-glass and glass-header seal areas.

Decapping and subsequent microscopic examination of the circuitry revealed smearing of the subject lead bond pad and scratching of the chip at the periphery outside the isolation barrier. A metallization defect was also noted at the adjacent diode (see Figure B-21). These defects were judged incidental to the operation of the circuit.

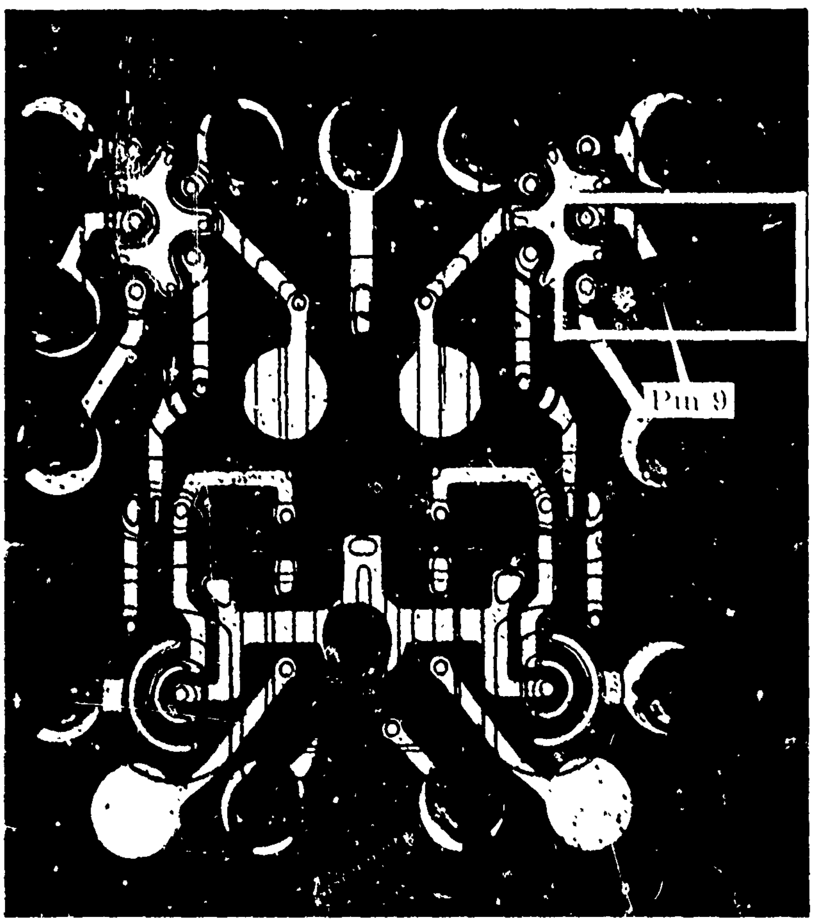


Figure B-21. Microcircuit, Dual Line Driver

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From these observations the most probable cause of failure can be stated as follows: A pinhole in the oxide layer at the P-N junction allowed moisture originating from the poor hermetic seal to collect and produce a leakage path. This mechanism was substantiated by recovery of the diodes reverse leakage measurement after baking. This failure is due to a defect introduced at the time of manufacture and therefore must be classified as a Type B failure.

p. Micromodule, Relay

Electrical tests indicated an open of the normally closed contacts between pins 8 and 10 in one of the two armature relays contained in the micromodule. Depotting of the device and subsequent microscopic examination showed a fracture of the armature swing pin (Figure B-22). Apparently the pivot pin was broken during part assembly. Later, after the storage period, the armature slid down and contacted the fracture burr. This prevented the armature from making the full swing, resulting in the inability of the contacts to close. Since the fractured pin occurred during manufacturing, this is a Type B failure.

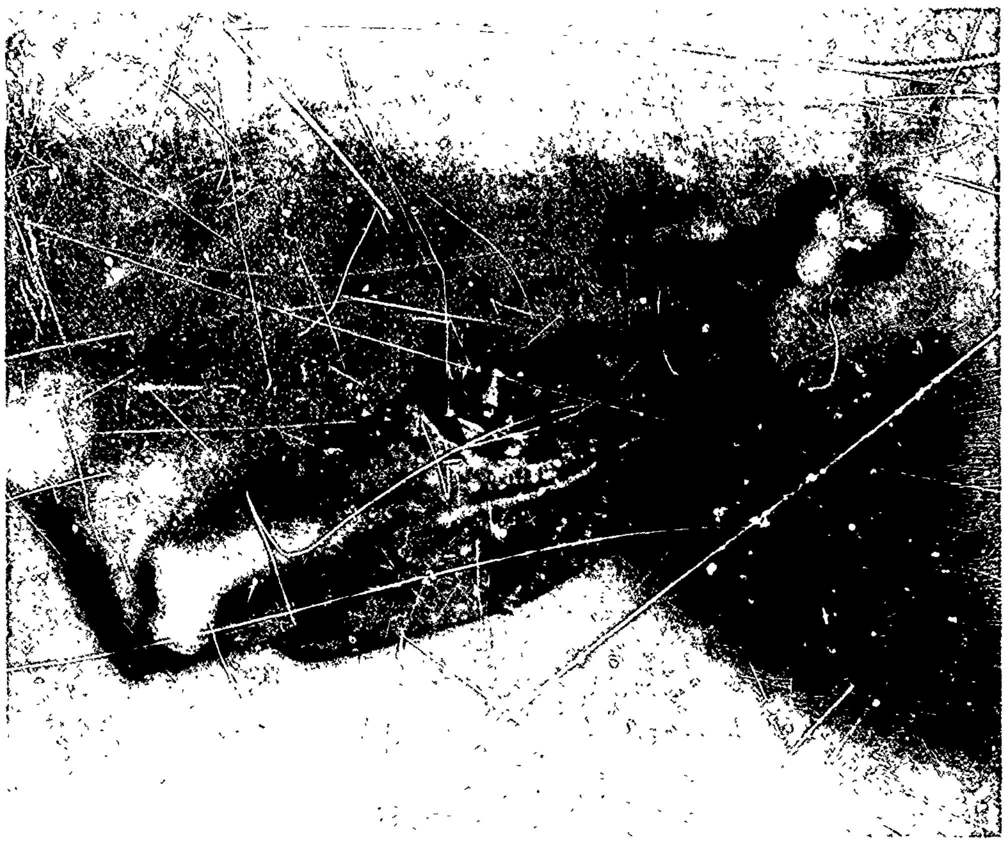

Figure B-22. Microcircuit, Relay Armature Swing Pin

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q. Micromodule, Half Adder

Tests showed an intermittent short to be occurring at pin No. 3 of the subject micromodule. Depotting revealed a broken weld of a microcircuit lead which had been connected to pin No. 3 (Figure B-23). Investigation revealed that the microcircuit lead to the external pin had been clipped too short and was welded at the tip. This weld, over a reduced contact area, caused an excessive concentration of heat resulting in a poor bond. Electrical contact was made but potting stresses and subsequent handling caused the bond to break. Sometimes a defect such as this is not apparent because the potting material will hold the pin in contact with the lead.

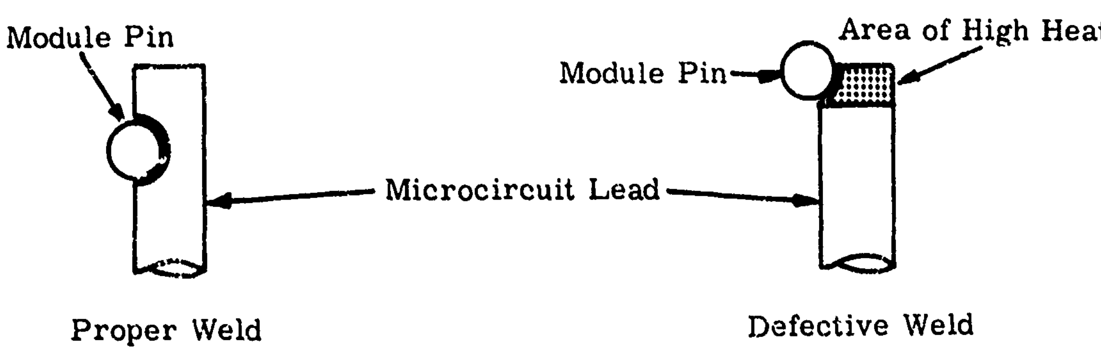


Figure B-23. Micromodule, Half Adder

r. Frequency of Occurrence of Failure Mechanisms

The frequency of occurrence of failure mechanism is presented in Table B-1.

TABLE B-I

Frequency of Occurrence Failure Mechanisms

| Percent | Quantity | Mode | Type | Part | Failure Mechanism |
|---|---|---|---|---|---|
| 17.0 | 4 | Short | B | 1 Microcircuit 3 transistors | Nonuniform photoetching, excess material |
| 13.0 | 3 | Current leakage | A, B | Tantalum capacitor | Defective seals, leakage, impurity introduction |
| 8.7 | 2 | Open | B | Transistor | Broken chip from initial fault in grown junction |
| 8.7 | 2 | High resistance | A | Metal film resistor | Hardening and loosening of conductive cement around lead-to-film junction |
| 8.7 | 2 | Open | B | Micromodule | Poor weld connection, internal open |
| 4.4 | 1 | Current leakage | A | Diode | Cracked glass seals, moisture introduction |
| 4.4 | 1 | Short | B | Diode | Excessive solder between leads on case |
| 4.4 | 1 | Open | B | Diode | Loose diode silicon clip, poor bonding |
| 4.4 | 1 | Short | A, B | Tantalum capacitor | Acid-etched hole in inner case |
| 4.4 | 1 | Open | A | Metal film resistor | Flake-off of metal film spiral |
| 4.4 | 1 | Short | B | Microcircuit | Loose chip of contact material in can caused by bonding procedure error |
| 4.4 | 1 | High resistance | A | Micromodule | Diode cracked and damaged due to potting shrinkage |
| 4.4 | 1 | Open | B | Transistor | Broken wire at bond, excessive pressure welded bond |
| 4.4 | 1 | Open | B | Micromodule | Improper assembly |
| 4.4 | 1 | Current leakage | B | Microcircuit | Seal leakage |

2. Nonoperating Failure Modes and Mechanisms

Listed in this subsection are nonoperating failure modes and mechanisms from the laboratory analysis and the literature described earlier.

1 Transistors

a Opens (poor welds and bonds) -

Lead wires loose from crystal, inadequate bond between lead and crystal;

Lead loose from crystal, too much bonding pressure as evidenced by pressure cracks around bonding area, and severed lead wire;

Lead loose, metal-to-metal or metal-to-silicon bonds open due to poor alloying, improper surface cleaning;

Lead loose from lead-in post, poor weld;

Die off header due to improper cleaning of die or header, poor header plating.

b Opens, Change of Parameters (due to physical and chemical degradation phenomenon) -

Corrosion from contamination introduced during manufacturing;

Purple plague, $AuAl_2$ formed when aluminum wires were bonded to gold-plated posts;

Black plague, formed when gold wires were bonded to aluminum metalization on top of silicon (with silicon acting as a catalyst to form a mechanically weak and poorly conducting black intermetallic compound);

Voiding in alloy region between wafer and header, which lowered power dissipation and caused hot spots that contributed to wafer cracking or fracture;

Degradation of current gain ($h_{fe}$) by migration of metallic atoms, change in surface state.

c Current Leakage, Shorting, and Channeling (from physical and chemical degradation phenomenon) -

Surface leakage from contamination on junctions and bad hermetic seal;

Surface breakdown conducting particles across the junction, improper junction cleaning;

Bulk leakage, conduction through a flaw in the silicon, usually a crack;

Silicon surface leakage, with contamination reaching surface of silicon by solid state diffusion through the oxide coating or by way of a porous oxide or flaw;

Water vapor in can resulting in conduction breakdown from water absorption on silicon wafer;

Contamination, causing channeling or surface inversion layer;

Improper etching processes in photo-etch devices; high leakage or shorts caused by mask misalignment; excess removal of oxide under junction during etching; lifting of photo resistant mask during etching to cause oxide removal; chipping or cracking die to expose junction.

2 Resistors

a Low-Power, Wirewound, Fixed Resistor -

Opens, change in resistance caused by internal moisture and alkaline corrosion due to deflective seals and/or porous coating;

Defective wire and terminations (terminal lead to cap, cap to resistance wire);

Change in resistance due to intermittent contact between wire and cap;

Intermittency due to poor internal welds;

Shorted turns and/or moisture causing change in resistance.

b Metal or Oxide Film Hermetically Sealed Fixed Resistor -

Opens, change in resistance, with failures being more prevalent in higher value resistors because the thinner films deteriorate faster;

Corrosion from seal failures admitting moisture and contamination;

Cracked cores from assembly stresses (substrate breakage) causing film rupture;

Film flaking caused by either poor adhesion of thick film in low value resistors, the differences in coefficients of expansion between the substrate and film, or the presence of foreign particles under the film from inadequate cleaning of the ceramic substrate;

Opens, change in resistance from oxidation (during testing) resulting from constriction on the film spiral (explained by the fact that when current passes through the constricted area, a hot spot is created to increase local oxidation and further constriction which continues with periodic testing and storage until the film cracks or vaporizes to cause an open);

Film diffusion that changed resistance;

$Ni_3Al$ precipitated out, leading to an increase and then a decrease in resistance.

c Carbon Fixed Resistor -

Increased resistance caused by defective seals, resulting in the absorption of moisture, which caused swelling of binder and separation of particles;

Fractures in case and defective terminals, causing increased resistance and eventual opens;

Increased resistance and opens caused by defective seals, which admitted moisture and led to electrolysis with (dc) electrochemical corrosion, gradual erosion.

d Carbon Composition Film, Variable Resistor -

Increased resitance, decline in insulation resistance, and eventual opens from defective seals, swelling of binder from moisture,

erosion of track, corrosion of terminal connection, and oxidation of metals.

e Wirewound General and Precision Variable Resistors -

Increased resistance and opens resulting from defective seals that permitted moisture penetration and subsequent corrosion of wire and oxidation of metal parts.

f. Fixed Tantalum Film Resistor -

Exhibited the same failure mechanisms as metal film and oxide film resistors. (Here, if the glass substrate contains alkaline contamination, it can cause the formation of $TaAl_3$ at the negative terminal resulting in resistance changes.)

3 Diodes

a Current Leakage and Shorts -

Moisture penetration, cracked glass cases and seals;

Contamination, permitting current leakage;

Variations in depletion layer width (reverse current instability);

Short caused by flaking of gold epoxy paste;

Short, excess solder outside silicon diode case, which caused intermittent contact between leads and solder.

b Opens, Poor Connections -

Voids in alloy bonding of silicon wafer to heat sink;

Voids in junction region, poor wafer orientation;

Crystal dislocations;

Open, whisker burnouts due to constriction on whisker causing localized heating and oxidation during testing. (This results in further constriction as a repetitive process until an eventual burnout of the whisker wire occurs.)

4 Capacitors

a Glass or Vitreous Enamel Capacitor -

Change in capacitance caused by moisture absorption through lead seals;

Case defects that caused changes in performance parameters;

Voids, geometrical variations, change in capacitance, possibility of shorts;

Alkali (Na) ion migration in the glass network

b Tantalum Foil Wet Capacitor -

High current leakage, internal contamination and/or electrolyte leakage through faulty seals;

Opens, loss of electrolyte or electrolyte attack on weld;

Capacitance loss caused by electrolyte vapor diffusion through seal;

External short due to electrolyte leaks that shorted lead to case.

c Solid Electrolyte ($MnO_2$) Tantalum Slug -

High leakage currents - shorts, defective seals, water vapor introduction and condensation;

Shorts caused by excessive internal lead solder dislodged during handling.

d Mylar Foil Capacitor

Shorts, crease in foil that caused an excessive voltage gradient;

e Tantalum, Solid and Sintered Slug, Wet Electrolyte -

High leakage, defective seal that admitted moisture which resulted in corrosion, impurity introduced during manufacturing that also induced corrosion;

Low capacitance, leaky seals that permitted loss of electrolyte.

5 Microelectronics

a Current Leakage -

Intermetallic formation at lead and chip bonds caused from the use of aluminum-gold combination;

Contamination introduced during manufacturing.

b Opens -

Poor bond between aluminum and dioxide caused by surface contamination and/or inadequate process control;

Poor bonds caused by too low or too high pressure in making lead attachment;

Open in aluminum caused by corrosive action of water vapor, soldering fluxes, or surface scratches.

c Shorts -

Migration

Chip loose in can, causing intermittent shorts (came from contact material and chipped off because of too much pressure in lead attachment).

d General Modes and Mechanisms -

Pinholes in metal-oxide capacitors;

Poor contact of metal to silicon substrate;

Pinholes or weaknesses in oxide under metalized areas;

Microscopic breaks in interconnections.

Improper hermetic seal

Separation of contact from interconnection along etched oxide step;

Oxide film between metal and substrate and subsequent poor or marginal alloying;

Pinholes or weaknesses in oxide, shorts in metal-to-oxide-silicon capacitors;

Interconnections, breaks, or pinholes leading to opens, caused by recrystallization of discrete regions of metal or by scratches introduced during assembly and test;

Purple plague on transistors at point of contact between aluminum and gold;

Black plague where gold and aluminum are located on silicon.

6 Micromodules

Failure mechanism in vacuum deposited areas, impurities, and undesirable reaction products, low density areas, pinholes, voids, high electrical resistance areas;

Failure mechanisms in plating processes and nonadherence to substrate, porosity, poor bonding, lack of uniformity, stressed and contaminated plating, property changes;

Failure mechanisms in capacitor material, specifically, nonuniform dielectric composition due to impurity content, and grain size, porosity, and distribution in electrode composition causing increased leakage current;

Failure mechanisms in silicon material, and crystal imperfection, impurity concentration and distribution, orientation, and oxygen content;

Failure mechanisms in joining such as variance in strength, metallurgical integrity, galvanic action, stability, thermal compression stability and bonding, ultrasonic welding, brazing, resistance welding, soldering chip to header bonding;

Failure mechanisms in resistance wire welding such as alloy change that led to changes in resistivity, residual stress, metallurgical properties, plus surface contamination, inclusions, reduced wire cross sections;

Failure mechanisms in epoxy molding such as shrinkage of potting which damaged component parts and led to moisture penetration, poor adhesion, voids, outgassing, blistering, cracking, physical property change;

Failure mechanisms in semiconductor surface stability, resulting in ionized impurities, silicon dioxide epilayer defects, impurity reactions, excessive current leakage, and channeling;

Thermal conductance, manifested as difference or change in heat transfer characteristics (coefficients) of materials;

Contamination such as foreign particles, adverse atmosphere, inclusions, residual ionic materials, metallic salts;

Material compatibility, incompatibility, differences in thermal expansion coefficients, single cell potential, silicon die cracking, corrosion reactions;

Package integrity, hermetic seal properties, joining-material interface, improper filler materials (silicon grease, etc.);

Inversion layers in transistor and diodes.

## APPENDIX C

## DESIGN NOTES

The summaries of collected data and failure analysis reports were given to applicable Martin Marietta specialists for review. These specialists have many years of experience in the design, evaluation, application, and test of parts. Drawing upon their knowledge and experience and using the results of this study, they prepared design notes on the part families for which the greatest quantity of data had been collected.

The notes in this appendix are intended as guides for obtaining the best possible parts for long-term storage applications.

1. Low-Power Silicon Diodes

   a. Catastrophic Storage Failure Rate

      Military Standard one fit; High Reliability, 0.3 fit.

   b. Failure Modes and Mechanisms

      1) Degradation Failures

Characterized by excessive reverse leakage current and high forward voltage drop. Surface contamination results in channeling because of:

1 Contamination sealed in diode package

2 Exposed junctions

3 Pinholes in oxide

4 Contamination remaining under oxide and on surface of the chip.

Preceding page blank

2) Catastrophic Failures

Opens and shorts caused by:

1 Improper location of internal whisker

2 Extra whiskers sealed within diode

3 Broken or deformed whiskers

4 Loose particles sealed within diode package

5 Cracked or fractured silicon chip

6 High current surge or voltage transient overstress.

c. Preferred Application

Long-duration storage at temperatures above 45°C should be avoided.

d. Preferred Procurement Practices, Incoming Inspection Tests

Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability. Parts should be equal to or better than prescribed by MIL-S-38103.

e. Preferred User Test and Checkout Practices

All circuits incorporating these parts should be designed to permit periodic checkout.

f. Preferred Vendor Manufacturing Practices

Manufacturing practices must include hermetic sealing; avoidance of extraneous impurities, acids, and cleaning solutions; maximum caution to ensure that adequate cleaning techniques are used.

g. Preferred Circuit Assembly Practices

Parts must be carefully handled and assembled to prevent seal breakage.

h. Other

Glass housing must be protected from strain when conformal coating materials are used for mounting on printed circuit boards. Glass meniscus must not be broken during handling. A diode mounted backward may

allow major damage to other components by resulting in inadequate protection from supplied power, etc.

2. Low-Power Silicon Transistors

a. Catastrophic Storage Failure Rate

Military Standard, three fits; High Reliability, 0.7 fit.

b. Failure Modes and Mechanisms

1) Degradation Failures

Degradation failures such as low beta gain, high reverse current, or silicon die surface contamination caused by:

1 Poor hermetic seal (glass to metal) caused by -

a Contamination or excess plating at well area

b Thermal mismatch of glass and metal

c Cracked header;

2 Exposed (nonpassivated) junctions caused by improper masking techniques;

3 Contamination -

a On silicon surface

b Under oxide due to poor cleaning techniques

c Pinholes in oxide.

2) Catastrophic Opens

Failures caused by:

1 Intermetalic [illegible] mation causing bonds to become brittle with age;

2 Voids between die and header causing cracked waifer from stress;

3 Poor metalization due to -

a Improper masking

b Surface contamination;

4 Poor bonding techniques caused by -

a Faulty wires

b Dull wedge bonder

c Inadequate heat at bond

d Misplaced bond.

3) Catastrophic Shorts

Failures caused by:

1 Lead sage from silicon die to post with age, causing short to can and/or header;

2 Foreign particles -

a Residue from photo resist process

b Weld splash

c Etching process particles not cleaned away;

3 Thermal runaway, high collector resistance path due to -

a Cracked die

b Voids under die.

c. Preferred Application

Long duration storage at temperatures above 45°C should be avoided.

d. Preferred Procurement Practices, Incoming Inspection Tests

Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability. Parts should be equal to or better than MIL-S-38103.

e. Preferred User Test and Checkout Practices

All circuits incorporating these parts should be designed to permit periodic checkout.

f. Preferred Vendor Manufacturing Practices

Must include hermetic sealing, oxidizing of aluminum before bonding of leads, avoidance of extraneous impurities, acids, and cleaning solutions.

g. Preferred Circuit Assembly Practices

Parts must be carefully handled and assembled to prevent seal breakage.

3. Variable Wirewound Trimmer Resistors

a. Catastrophic Storage Failure Rate

Military Standard, 5 fits; High Reliability, 5 fits.

b. Failure Modes and Mechanisms

1 Opens caused by defective wire and/or terminations;

2 Opens caused by internal moisture corrosion resulting from poor seals;

3 Change in resistance caused by shorted turns and/or moisture;

4 Intermittent opens due to wiper or element corrosion and contamination of element.

c. Preferred Application

Recommended for dormant operation and storage and wherever a fixed star value (see Glossary) cannot be selected.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Vendor should be selected from sources qualified for MIL-R-27208 or MIL-R-39015 practices;

2 Power burn-in conditioning should be 100 percent at a minimum of 200 percent rated power at room temperature (25°C);

3 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability;

4 Sources should be required to supply 1 year of sequential periodic MIL spec test data prior to being considered.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

1 All internal terminations should be resistance welded;

2 All types must have stops, clutches, and O-ring seal with terminals sealed and 100 percent lock test required;

3 Elements should be continuous filament without intermediate splices;

4 Minimum resistance wire diameter of 1 mil should be used for element, with maximum value of 10 kilohms and minimum value of 100 ohms;

5 Terminal lead of knurled configuration should be molded into case.

g. Preferred Circuit Assembly Practices

1 Parts should be assembled so that date code may be read;

2 Terminal pins shall not be bent during assembly.

4. Low-Power Wirewound Accurate Resistors

a. Catastrophic Storage Failure Rate

Military Standard, 5 fits; High Reliability, 1 fit.

b. Failure Modes and Mechanisms

1 Opens caused by defective wire and/or terminations;

2 Opens caused by internal moisture, corrosion resulting from poor seals and/or porous coating;

3 Change in resistance caused by shorted turns and/or moisture.

c. Preferred Application

Recommended for dormant operation and storage.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Vendor should be selected from sources qualified for MIL-R-39005;

2 Power burn-in conditioning should be 100 percent at a minimum of 150 percent rated power at 125°C for 250 hours;

3 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability;

4 Sources should be required to supply 1 year of sequential periodic MIL spec test data prior to being considered.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

1 All internal terminations should be resistance welded;

2 Elements should be a continuous filament without intermediate splices;

3 All cross-over points should have supplementary insulation;

4 Minimum diameter of 1 mil should be used for element;

5 Windings must be protected by a resilient material before encapsulation;

6 Terminal lead connection to bobbin should be by molded into lead construction or combination of knurled force fit, and end cap.

g. Preferred Circuit Assembly Practices

1 Bend leads 1/8 inch minimum from ends of meniscus;

2 Support leads between bend and body of resistor when bending;

3 Assemble parts so that date code may be read;

4 Do not allow components to be twisted after assembly.

5. Hermetically Sealed Metal Film Resistor

a. Catastrophic Storage Failure Rate

Military Standard, one fit; High Reliability, 0.2 fit.

b. Failure Modes and Mechanisms

1 Opens and changes in resistance caused by moisture and contamination because of seal failures;

2 Opens and intermittents caused by cracked cores resulting from assembly stresses;

3 Resistance increases and opens resulting from film flaking caused by poor adhesion of thick film in low value resistors (low ohms per unit square).

c. Preferred Application

1 Recommended for dormant operation and storage where stability with time is required;

2 Recommended that resistors having only the following values be utilized because of the film thickness problem:

$100\Omega$ to 150 $K\Omega$ for 1/8 W
$100\Omega$ to 1 $M\Omega$ for 1/2 W.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Vendor should be selected from sources qualified for MIL-R-10509 and MIL-R-55182.

2 Power burn-in conditioning 100 percent;

3 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability;

4 Tap test for cracked cores;

5 Polarized light test for glass strain (longitudinal stress);

6 Hermetic seals should be 100 percent inspected for $1 \times 10^{-8}$ cc/s leakage per MIL-STD-202.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

1 No conductive cements should be used;

2 Welding of resistance lead terminations to end caps preferred;

3 Glass to metal fusion seal is the preferred construction;

4 Exercise control of spiral cut and width;

5 Spiral length should be a minimum of 70 percent of effective length between caps;

6 Regular width of ribbon, 0.006 min - absolute min, 0.004;

7 Regular width of helical cut, 0.005 min - absolute min, 0.003.

g. Preferred Circuit Assembly Practices

1 Visual inspection for glass seal breakage during assembly,

2 Bend leads 1/8 inch minimum from ends of meniscus;

3 Support leads between bend and body of resistor when bending;

4 Assemble parts so that date code may be read,

5 Do not allow components to be twisted after assembly.

6. Low-Power Wirewound Resistors

a. Catastrophic Storage Failure Rate

Military Standard, 5 fits, High Reliability, 1 fit.

b. Failure Modes and Mechanisms

1 Opens caused by internal moisture and alkaline corrosion resulting from poor seals and/or porous coating;

2 Opens caused by defective wire and/or terminations (terminal lead to cap, cap to resistance wire);

3 Change in resistance caused by contact between wire and edge of cap when weld is not located near inner edge of cap;

4 Intermittency as a result of poor internal welds.

c. Preferred Application

Only resistors with vitreous enamel coating are recommended for long duration storage.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Vendor shall be selected from sources qualified for MIL-R-39007;

2 Power burn-in conditioning 100%; at 125°C for 250 hours;

3 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

1 Use oxidized wire on all resistors utilizing 0.002 or smaller resistance wire, with element wire welded to end caps close to edge;

2 Vitreous enamel should completely encapsulate cap and lead interface;

3 Only single layer windings should be permitted.

g. Preferred Circuit Assembly Practices

1 Bend leads 1/8 inch minimum fron ends of meniscus;

2 Support leads between bend and body of resistor when bending;

3 Assemble parts so that date code may be read;

4 Do not allow components to be twisted after assembly;

5 Use either epoxy or foam conformal coating for protection from moisture;

6 Control conformal coating thickness and location of resistor above board to avoid damaging effects of thermal stresses.

7. Glass or Vitreous Enamel Capacitor

a. Catastrophic Storage Failure Rate

Military Standard, 0.2 fit; High Reliability, 0.05 fit.

b. Failure Modes

Moisture absorption through lead seals or case defects causing changes in performance parameters.

c. Preferred Application

Recommended for dormant operation and long term storage, and where capacitance stability, high insulation resistance, and low dissipation factors are required.

d. Preferred Procurement Practices, Incoming Inspection Tests

Procure only from sources whose process controls have been approved and whose products continue to demonstrate, with documentation, a consistently high reliability; 100 percent visual inspection for seals and case defects.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

Ensure that seals and cases are free of defects.

g. Preferred Circuit Assembly Practices

1 Bend leads 1/8 inch minimum from ends of case;

2 Mounting by leads is not recommended;

3 Careful handling required to prevent seal breakage and case damage.

8. Solid Tantalum Capacitor

a. Catastrophic Storage Failure Rate

Military Standard, 3 fits; High Reliability, 0.2 fit.

b. Failure Modes

1 Excessive current leakage or short caused by defects in film;

2 Excessive current leakage caused by moisture penetrating seal and condensing on inside glass surface;

3 Shorts caused by dislodging of excessive internal lead solder during handling.

c. Preferred Application

1 Recommended for long-duration storage and dormant operation;

2 Not recommended for use in timing circuits;

3 Circuit design should include a minimum of 3Ω/volt effective circuit resistance needed to protect against current surges and voltage reversals.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability;

2 Vendor should be selected from sources qualified for MIL-C-39003;

3 Inspect 100 percent for dc leakage;

4 Check samples for capacitance and dissipation factor;

5 Hermetic seals should be 100 percent inspected for $1 \times 10^{-8}$ cc/s leakage per MIL-STD-202;

6 Procure only from sources who form their own tantalum pellet and tantalum pentoxide;

7 Conduct 100 percent radiological inspection for excessive lead solder and displaced anodes.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred Vendor Manufacturing Practices

1 Use highest purity tantalum available;

2 Maintain rigid control over processes used in forming pellet, sintering, and formation of dielectric;

3 Assemble in a clean atmosphere with particular emphasis on soldering leads and sealing;

4 Ensure that anode assembly is free of all electrolyte and cleaning solutions;

5 Round edges of slug to avoid thin spots in oxide.

g. Preferred Circuit Assembly Practices

1 Polarity of polarized capacitors must be observed;

2 Bend leads 1/8 inch minimum from ends of lead welds;

3 Use heat sinks or equivalent protection when soldering small case sizes;

4 When mounted by leads, protect anode lead from mechanical strain.

9. Wet Tantalum Foil Capacitor

a. Catastrophic Storage Failure Rate

Military Standard, 20 fits; High Reliability, 2 fits.

b. Failure Modes and Mechanisms

1 High leakage current caused by internal contamination and/or electrolyte leakage;

2 Opens caused by loss of electrolyte or electrolyte attack on weld;

3 Capacitance loss as a result of electrolyte vapor diffusion through seal;

4 External shorts caused by electrolyte leaks that short lead to case.

c. Preferred Application

1 Not recommended for long duration storage because of state-of-the art seal problems;

2 Use only if space limitations and circuitry require a high capacitance and voltage ratio to unit volume and where capacitance stability is not a consideration;

3 Recommended in circuits where transient voltage spikes may be encountered;

4 Do not use if there are periodic voltage reversals (polarized);

5 Should not be used at greatly reduced voltage levels during dormant operation and then returned to rated load.

d. Preferred Procurement Practices, Incoming Inspection Tests

1 Procure only from sources whose process controls have been approved and whose products continue to demonstrate a consistently high reliability (minimum quality must be equivalent to MIL-C-39006),

2 Inspect 100 percent for dc and electrolyte leakage;

3 Periodic routine dissection of samples to check for manufacturing defects;

4 Check samples for capacitance and dissipation factor.

e. Preferred User Test and Checkout Practices

All circuits incorporating these capacitors should be designed to permit periodic checkout.

f. Preferred Vendor Manufacturing Practices

Use good quality material and high purity foil assembled in a white room atmosphere with distinct process control over dielectric forming and sealing.

g. Preferred Circuit Assembly Practices

1 Polarity of polarized capacitors must be observed;

2 Bend leads 1/8 inch minimum from ends of welds;

3 Use heat sinks or equivalent protection when soldering small case sizes;

4 Do not mount by leads or in areas subject to high temperatures.

10. Microcircuits

Because of the replication of the silicon monolithic process in manufacturing current digital and linear microcircuits this design note has been so developed as to apply to all types of digital and linear microcircuits.

a. Catastrophic Storage Failure Rate

Military Standard Equivalent, 70 fits
High Reliability Equivalent, 10 fits

b. Failure Modes

To establish a convenient and expeditious reference to monolithic microcircuit failure modes, the failure modes presented in Table VII - XXVIII of MIL-HDBK-217A have been revised and supplemented to reflect dormant operating and storage program experience. This revision is shown as Table C-I and can be used as a replacement for Table VII-XXVIII of MIL-HDBK-217A. Additional information can be found in a Raytheon report (Reference 51), an Autonetics report (Reference 52), and in RADC report, reference 53.

c. Preferred Application

Reliability in microcircuit applications may be enhanced by use of redundancy or standardization. To be successful, the redundancy technique requires a knowledge of the various failure modes and the variation of the failure modes among different parts suppliers. Also, redundancy increases weight, power requirements, size, and the complexity of the system. Standardization is a very effective method for improving reliability if for no other reason than that it minimizes the number of different components. This minimization allows standardization of the production line process control which effectively improves reliability.

Transient voltages (without current limiting) can be damaging to microcircuits; therefore, transient suppression provisions must be made for dormant operation, normal operation and during test and checkout.

d. Preferred Procurement and Vendor Manufacturing Practices

A Military Standard covering this paragraph is to be issued by December 1967. Until that time, References 54, 55, 56 and 67 should be used as guides.

e. Preferred User Test and Checkout Practices

Based on current experience, no special practices or restrictions are required.

f. Preferred System Assembly Practices

The majority of microcircuits are packaged in TO-5 type cans or flat packs. There has been considerable controversy over the best type of external interconnection to use when assembling microcircuits. Both

soldering and welding have been used extensively, and the type of interconnection chosen must be compatible with the packaging configuration. Most recently, evidence has shown new welding techniques to be very promising for improving the reliability of lead tie down (Reference 56). The use of miniature connectors should be discouraged, since the connector is often less reliable than the integrated circuit itself.

During mechanical mounting or machine lead bending of microcircuits, extreme care should be exercised to prevent destroying the hermetic seal. Tests should be instituted to assure hermeticity after any processing step that may damage the seal.

Proper handling procedures should be followed when cutting leads. High shock levels, which may cause damage, can be generated with hard surface carbide cutters. Shear action cutters, properly used, nullify this problem.

Periodic routine dissection of samples should be performed by the user to check for manufacturing defects.

TABLE C-I

Some Microcircuit Modes of Failure

| Time Dependent Modes | | | Non-Time Dependent Modes | | |
|---|---|---|---|---|---|
| Cause | Effect | Control | Cause | Effect | Control |
| Etchant or other processing materials which have not been completely removed by cleaning. | Opening of aluminum conductor pattern. | Extreme care in cleaning operations, detected by life testing. | Improper wafer cleaning, insufficient bonding temperature for pressure, insufficient conductor thickness. | Open bonds - electrolysis, gold leads pull away from aluminum conductor pattern, open metallization patterns. | Care in cleaning and bonding operations and adequate conductor thickness detected by 20,000g acceleration test. |
| Moisture content within the package. | Shorts near surface scratches or steps in surface passivation where current densities in the pattern are high. Open aluminum interconnects due to formation of hydrated alumina ($Al_2O_3$). | Low moisture environment for sealing of packages, detected by life testing. | Over bonding - excessive bonding temperature and pressure. | Bond, aluminum conductor and part of the surface passivation layer are removed from the device surface. | Control of bonding temperature and pressure-detected by 20,000g acceleration test. |
| Wafer scribing process, accelerated by die bonding operation. | Progressive cracking or chipping of substrates resulting in shorts and opens, respectively. Scribing too close to the bond with resultant shorts. | Extreme care and visual inspection during scribing and die bonding operations - detected by life tests. | Improper design fabrication or use of masks. | Open contacts, high contact resistance, shorted junctions. | Improve techniques for mask design and alignment - detected by electrical performance tests. |
| Formation of gold aluminum and gold aluminum-silicon compounds around bonds, activated by excessive bonding or sealing temperatures. | Decreased bond strength, high impedance, brittle joints. | Adequate conductor thickness, strict control of bonding and sealing temperatures, or use of different materials detected by extensive bake followed by shock or centrifuge test. | Improper packaging, labelling and the inclusion of junk (glass or gold particles, etc.,) in the package. | Shorts, intermittent operation, misapplication of the device. | Improve workmanship and in-process inspections. |
| Tensile fracture and melting due to abrupt changes in the level of surface passivation near contact areas, where high current densities are probable. | Open in aluminum conductor path, particularly around contact areas. | Process control and provision for adequate conductor thickness-detected by life tests. | Poor lead dress or excessive lead length due to poor layout of aluminum terminal pads with respect to the package leads. | Open and shorted internal leads, intermittent operation. | Adhere to proper layout and bonding procedures. Detected by shock, vibration and centrifuge tests in the y2* direction prior to electrical test. |
| Scratches and smears on the surface materials caused by faulty tools or mishandling. | Open aluminum conducting paths, open bonds, shorts between aluminum paths. | Improved handling methods and procedures and increased visual inspection. | Poor sealing which permits moisture to enter the package. | Intermittent or degraded operation. | Initiate improved sealing procedures and methods - detected by leak tests. |
| Pin holes and entrapped impurities in the passivation layers. | Electrical breakdown in surface passivation from the aluminum conductor to component areas in the silicon. | Control of surface oxidation thickness and possibly, oxide growth rate detected by life testing. | Poor aluminum adhesion. | Open bonds. Bond and aluminum lift together with no adherence to the passivation layer. | Care in cleaning operations and adequate conductor thickness - detected by shock, vibration and centrifuge tests. |
| Faulty oxide removal. | Open caused by formation of insulating layer between aluminum and silicon in the passivating layer window. | Process control - detected by burn-in or baking. | Voids in die mounting junction. | Hot spots on die. | Evaporation of gold to die bottom, followed by sintering above the AuSi eutetic temperature† and then wetting with another layer of gold.<br>*See glossary<br>†Duration and temperature must be closely controlled since excessive gold penetration may cause electrical degradation. |
| Aluminum migration into silicon along lines of crystal imperfections. | Electrical degradation. | Proper starting material - detected by life testing, burn-in or baking. | Aluminum pads too small for bond or misalignment of bond and pad. | Open bonds. | Improve workmanship and in-process inspection. |
| Surface contamination prior to oxide growth due to gaseous or ionic contamination. | Inversion/channeling resulting in low gain or low breakdown, thus degrading electrical characteristics. | Process control and guard ring - detected by burn-in or voltage stressing. | Severe thermal shocks during processing (cooling rapidly from 1300°C to room temperature). | Cracks in bulk silicon or silicon oxide crazing. | Process control - detected by in-process inspection. |
| | | | Contamination on top of the silicon dioxide due to moisture, weld gases, gas absorption. | Electrical degradation due to high leakage or soft breakdowns. | Process control and proper seal - detected by electrical performance tests. |
| | | | Overetched metalization. | Opens in aluminum conductor path. | Adherence to proper layout and bonding procedures (detected by shock, vibration and centrifuge tests). |

## APPENDIX D

### DETERMINATION OF WEIGHTED SEMILOGARITHMIC LINEAR REGRESSION PLOT FOR FIGURE 2

It was desired to establish the mathematical expression for the observed data points of Table XVI. A weighted semilogarithmic regression line or plot was best suited for this purpose. The y values represent the observed catastrophic failure rates (in fits) and the x values the reciprocal of absolute temperature (1/°K). Maximum weight was given to the 25°C point since it contained more than 96 percent of the experience part hours. According to the postulate developed in Chapter 16 of Reference 71, the weighted regression line should pass through this point x = 335, y = 20.6 and the point representing the mean of the x's and the y's. Since the y values were plotted on the log scale (Figure 2) the following method was used:

| Determine $\bar{y}$ ($\lambda$) $y \times 10^{-2}$ | | Determine $\bar{x}$ $\left(\frac{1}{°K}\right)$ $x(\times 10^{-5})$ |
|---|---|---|
| ln 0.206 | = -1.57987 | 335 |
| ln 11.8 | = 2.46810 | 250 |
| ln 16.6 | = 2.80940 | 235 |
| ln 35.1 | = 3.55820 | 221 |
| ln 59.7 | = 4.08933 | 210 |
| ln 140 | = 4.94164 | 190 |
| ln 236 | = 5.46383 | 174 |
| | 21.75063 | 1615 |

$$\frac{21.75063}{7} = 3.10723 \qquad \frac{1615}{7} = 231 \times 10^{-5}$$

$$\text{antilog } 3.10723 \doteq 20.30$$

$$\bar{y} \times 10^{-2} = 20.30$$

$$\bar{y} = 2030 \qquad \bar{x} = 231 \times 10^{-5}$$

The line passing through the 25°C point and the mean point was now extended to the y intercept ($y = 6 \times 10^7$). The equation for the weighted semilogarithmic regression line was determined by the method shown on pages 114 to 116 of Reference 72. The relationship desired is an exponential equation of the form

$$y = ae^{mx}.$$

The intercept, a is read at the point where the line cuts the ordinate at $x = 0$. The width of one cycle of semilog paper is a constant equal to ln 10 - ln 1 = 2.3026. Thus, it is convenient to take this distance for the side of the triangle used to measure slope. Calling the base of this triangle $x^1$, then:

$$m = \frac{2.3026}{x^1}$$

or in this instance

$$m = \frac{2.3026}{52 \times 10^{-5}} = 4428.$$

Hence, the equation for the combined data regression line with negative slope shown in Figure 2 is

$$y = 6 \times 10^7 e^{-4428x}$$

The equation was then checked as follows:

| °C | X | -4428x | $e^{-4428x}$ | $y_{cal}$ | $y_{obs}$ |
|---|---|---|---|---|---|
| 25 | $336 \times 10^{-5}$ | -14.878 | $0.344 \times 10^{-6}$ | 20.6 | 20.6 |
| 50 | $310 \times 10^{-5}$ | -13.727 | $0.107 \times 10^{-5}$ | 64.2 | None |
| 75 | $287 \times 10^{-5}$ | -12.708 | $0.298 \times 10^{-5}$ | 179 | None |
| 100 | $268 \times 10^{-5}$ | -11.867 | $0.692 \times 10^{-5}$ | 415 | None |
| 125 | $251 \times 10^{-5}$ | -11.114 | $0.147 \times 10^{-4}$ | 882 | 1,180 |
| 150 | $236 \times 10^{-5}$ | -10.450 | $0.287 \times 10^{-4}$ | 1,722 | 1,660 |
| 175 | $223 \times 10^{-5}$ | -9.874 | $0.513 \times 10^{-4}$ | 3,078 | 3,510 |
| 200 | $211 \times 10^{-5}$ | -9.343 | $0.873 \times 10^{-4}$ | 5,238 | 5,970 |
| 250 | $191 \times 10^{-5}$ | -8.457 | $0.212 \times 10^{-3}$ | 12,720 | 14,000 |
| 300 | $175 \times 10^{-5}$ | -7.749 | $0.431 \times 10^{-3}$ | 25,860 | 23,600 |

## REFERENCES


1. Gurnick, A., "Results of Search for Storage Degradation Data on Component Parts," IDEP No. 347.60.00.00-B1, May 1964

2. "Disposition of Four-Year-Old Tantalum Capacitors," IDEP No. 152.76.40.00-K9-01, May 1965

3. "Reliability of Microelectronics," IDEP No. 515.00.00.00-G4-01, May 1965

4. "Resistors, Fixed, Carbon Film," IDEP No. 651.20.08.08-R2-01, April 1965

5. "Resistors, Fixed, Metal Film, Precision," IDEP No. 651.55.03.14-E7-01, August 1964

6. "Resistors, Variable, Wirewound," IDEP No. 661.70.51.40-E3-01, June 1965

7. "Semiconductor, Diodes, Zener, Silicon," IDEP No. 741.40.40.00-E3-04, GE-RG0 - Syracuse, June 1965

8. Pershing, Dr. A. V., "Semiconductors and Their Failure Modes," IDEP No. 742.00.00.00-E9-10, October 1963

9. "Semiconductors, Transistors, Silicon," IDEP No. 742.10.30.00-S3-14.

10. "Defective Carbon Resistor," IDEP No. 651.20.08.00-X9-01.

11. "Easterday, J. L., Bowman, R. G., Gahm, W. L., and Spradlin, B. C., "Reliability of Integrated Circuits Used in Missile Systems," Redstone Scientific Information Center, October 1964

12. Tanner, T. L., "Operational Reliability of Components in Selected Systems," 1966 Annual Symposium on Reliability, pp 198-211

13. "Reliability Prediction Adjustment Factors," Electronic Systems Reliability Committee of the Electronic Equipment Technical Committee of Aerospace Industries Association, National Standards Association, Inc., EETR Report No. 28

14. Chisham, S/Sgt W. E., "Nike-Ajax Minimum Serviceable Life Determination," WSMR-TM-638, August 1959

15. McGlothlin, W. H. and Stoller, D. S., "Age and Usage Factors Affecting Missile Reliability," Rand Report RM-2560 (R64620), 15 April 1960, Confidential

16. "A Study of Dormant Missile Systems," Vol 1, Summary, Technical Report BSD-TR-66-52, February 1966, Secret

17. "A Study of Dormant Missile Systems," Vol 2, Technical Findings, Technical Report BSD-TR-66-52, February 1966, Secret

18. "A Study of Dormant Missile Systems," Vol 4, Appendix, Technical Report BSD-TR-66-52, February 1966, Secret

19. "Reliability Study Cites Transistor Duty Cycle," Aviation Week and Space Technology, pp 86-89, 19 April 1965

20. Lathan, B. F., "Evaluation of Silicon Metallic Rectifiers," Final Engineering Report, ARF Project, E089, 31 March 1961

21. Lathan, B. F., "Evaluation of Silicon Metallic Rectifiers," Final Engineering Report, ARF Project, E107, 31 October 1961

22. Martin Marietta Corporation, OR 3482, "Reliability Assessment of Stockpiled GAM-83A Nose Sections," Orlando, Florida, September 1963. Confidential

23. Martin Marietta Corporation, OR 6596, "Pershing Storage Reliability Report," Orlando, Florida, July 1965, Confidential

24. Zoller, V. L., "Pershing Product Quality Evaluation Program FY '65 Final Report," OR 6591, Martin Marietta Corporation, Orlando, Florida, 1965

25. Steen, E. T., "Missile 307 Age and Deterioration Test," OR 1990 Series, Martin Marietta Corporation, Orlando, Florida, December 1961, Secret

26. Dillard, R. B., "Results of BIRDiE Card Test After Storage," Martin Marietta Corporation, Orlando, Florida, ICM, 12 January 1965

27. Mulvihill, R. J., Myers, W. J., and Watson, H. S., "Compilation and Analysis of Calendar-Age-Related Data for Hydraulic System Components," PRC R-377, Systems Technology, Inc., Inglewood, California, 15 August 1963

28. Ficchi, R. F., "How Long-Term Storage Affects Reliability," Electronic Industries, pp 42-48, March 1966

29. Kamins, Milton, "Determination Checkout Intervals for Systems Subject to Random Failures," Rand Report RM-2578, AD 247-383, 15 June 1960

30. McCarthy, W. J. and Kritter, E. L., "Application of Nonoperating Part Failure Rate," U. S. Army Presentation, Reliability Aspects of Dormancy and Storage, 8 December 1965, Confidential

31. TRW Space Technology Laboratories, "Consolidated Aging Study Program for the LGM-30 Weapon System," Vol 1, Summary, Redondo Beach, California, 30 June 1965

32. Newman, Capt J. D. and Lauck, Lt R. E., "Dormant Readiness Studies for ICBM Systems," 65-BSRA-248, Ballistic Systems Division, Air Force Systems Command, United States Air Force, Norton AFB, California, Secret

33. Shackford, R. W., "A Study of Dormant Missile Systems," 66-BSRA-110, Ballistic Systems Division, Air Force Systems Command, United States Air Force, Norton AFB, California, Secret

34. Newbold, Capt D., "Operational Life Surveillance Aspects of Reliability for the Minuteman Weapons System," U. S. Army Presentation, Reliability Aspects of Dormancy and Storage, 8 December 1965, Confidential

35. Black, R. O. and Conger, L. R., "The Need for Valid Storage Reliability Data," U. S. Army Presentation, Reliability Aspects of Dormancy and Storage, 8 December 1965, Confidential

36. Lapidus, P., "Munitions Command Reliability Program to Support the Nuclear Weapons Wooden Warhead Concept," U. S. Army Presentation, Reliability Aspects of Dormancy and Storage, 8 December 1965, Confidential

37. Hadley, W. L., "Nonoperating Reliability Data and Its Applications to Systems," U. S. Army Presentation, Reliability Aspects of Dormancy and Storage, 8 December 1965, Confidential

38. Bauer, J. A., "Semiconductor Failure Mechanisms - Operation and Storage Modes," OR 8044, Martin Marietta Corporation, Orlando, Florida, February 1966

39. Katz, Irving, "A New Concept of Planned Inspections," Operations Analysis Working Paper No. 13, Headquarters, Air Force Logistics Command, July 1965

40. "Failure Rate Data Handbook," SP 63-470, Vol 1A, 1B, 2, 3, and 4, FARADA, Corona, California, 1 June 1962

41. Dosien, R. W., "Technical Evaluation Project for Improved Tartar Missiles," FMSAEG, Corona, California, 30 March 1965, Confidential

42. Natrella, Mary G., "Experimental Statistics," National Bureau of Standards Handbook 91, Washington, D. C., 1 August 1963

43. Lowe, R. R. and Warshaw, M., "The Reliability of Ground-Based Digital Computers," Rand-Corp., AD 467-808, June 1965

44. "Minuteman High Reliability Component Parts Demonstrated Failure Rate," Graphic Status Report No. 3, Autonetics, T4-776.02/3111, IDEP No. 347.20.00.00-C1-03

45. Goldberg, M. F. and Vacarro, J., "Physics of Failure in Electronics," RADC Vol 2, AD 434-329

46. Vacarro, J., "Reliability Physics Notebook," RADC-TR-65-330, October 1965

47. Dietz, R. E., "Preferred Numbers - A Standardization Tool," IEEE Transactions on Aerospace, Vol AS-1, No. 2, pp 238-242, August 1963

48. NAVWEPS 00-65-502, Handbook Reliability Engineering, Section 2-3-2, 1 June 1964

49. Gott, P., "Reliability Report on Planar Epitaxial Microcircuits," Philco Corporation, August 1966

50. "Status Report of Integrated Circuit Reliability," Revision No. II, Motorola, January 1966

51. Eliot, C. C., "Microelectronics Reliability," Proceedings 1967 Annual Symposium on Reliability, pp 349-355

52. Nowak, T. J., "Reliability of Integrated Circuits by Screening," Proceeding 1967 Annual Symposium on Reliability, pp 365-375

53. Hilow, R. C., O'Connel, E. P., and Tamburrino, A. L., "Modern Approaches to Microcircuit Reliability Assessment," Proceedings 1967 Annual Symposium on Reliability, pp 625-632

54. Partridge, J., Hanley, L. D., and Hall, E. C., "Progress Report on Attainable Reliability on Integrated Circuits for System Application," MIT Instrumentation Lab, November 1964

55. Partridge, J., Hanley, L. D., and Hall, E. C., "The Application of Failure Analysis in Procuring and Screening of Integrated Circuits," MIT Instrumentation Lab, October 1965

56. "Microelectronic Device Data Handbook," NASA Parts Publication NPC 275-1, August 1966 Edition

57. Naresky, J. J., "Reliability and Maintainability Research in the U. S. Air Force," Annals of the 5th Reliability and Maintainability Conference, AIAA, July 1966

58. "Dormant Operating and Storage Effects on Electronic Equipment," Technical Report, RADC-TR-66-348, AD 801-335, October 1966

59. "Reliability Stress and Failure Rate Data for Electronic Equipment," MIL-HDBK-217A

60. "Military Standard Reliability Prediction," MIL-STD-756A, Defense Supply Agency, Washington, D. C., May 1963

61. Van Hoorde, G. R., "Reliability of Microelectronics," IDEP No. 515.00.00.00-G4-01, February 1966

62. Van Hoorde, G. R., "Microelectronics Survey," TRW Systems, September 1965

63. Brown, A. R., "Burn-in and Screening for Integrated Circuits," 7th Annual New York Conference on Reliability, 20 May 1966

64. Reiche, H., "The Behavior of Electronic Components at Low Operating Stress Levels," Microelectronics and Reliability, Pergamon Press, Vol 5, pp 1-6, 1966

65. Bashara, N. M., "A Survey of Conduction Mechanisms in Very Thin Films," IEEE CP-11, March 1964

66. Schwartz, S., "Integrated Circuits in Action - Part 4, Postmortems Prevent Future Failures," Electronics, 23 January 1967

67. "Minuteman Microelectronics Application Guide," TRW Systems, IDEP No. 515.00.00.00.G4-02, August 1966

68. Cherney, R. W., "Reliability Prediction in Design of Microelectronic Aerospace Systems," Seventh Annual New York Conference on Electronic Reliability, May 1966

69. Hadley, W. L. and Schiavone, D., "Toward Storage Reliability for Electronic Systems," Space/Aeronautics, February 1967

70. Bauer, J., Hadley, W., and Dietz, R., "Dormant Operating and Storage Effects on Electronic Equipment and Part Reliability," RADC-TR-65-323, Martin Marietta Corporation, Orlando, Florida, November 1965

71. Moroney, M. J., "Facts From Figures"

72. Rule, J. T. and Watts, E. F., "Engineering Graphics," McGraw Hill, 1951

## BIBLIOGRAPHY


Adams, J. and Workman, W., "Some Aspects of Reliability," pp 1624-25, Proceeding of IEEE, December 1964

Alelyunas, P., "Reliability," Space/Aeronautics, October 1964

Allen, D. R., "Minuteman High-Reliability Component Parts Demonstrated Failure Rates," TA-776.02/3111, April 1965

Anderson, G. P. and Erickson, R. A., "Failure Modes in Integrated and Partially Integrated Microelectronic Circuits," Physics of Failure in Electronics Vol 2, AD 434-329, pp 498-524, 6 March 1964

Anderson, J. R. and Saunders, J. B., "Improving Reliability of Microcircuit Connectors," Electro-Technology, October 1962

Avil, H. Maronde, C. and Kirvida, L., "Non-Destructive Reliability Screening of Electronic Parts, Using RF Noise Measurements," RADC-TR-65-71, AD 618-469, Griffiss AFB, New York, January 1965

Best, G., Endicott, H. S., McLean, H., and Walsh, T. M., "Accelerated Testing of High Reliability Parts," November 1965

Belser, R. B., Hicklin, W. H., and Young, R. A., "Quartz Crystal Aging Effects," Georgia Institute of Technology, AD 434-674, November 1963

Bild, Charles F., "Failure From a Materials Point of View," Tenth Annual Symposium on Reliability and Quality Control, pp 330-337, January 1964

Blakemore, G. J., "Semiconductor Reliability," Quarterly Report No. 3, AD 403-120, April 1963

Bohrer, J. J. and Lewis, C. W., "The Aging Mechanisms of Metal Film Resistors," Physics of Failure in Electronics Vol 2, AD 434-329, pp 338-348, 6 March 1964

Brauer, Joseph B., "Microelectronics and Reliability Assessment," Electronic Industries, April 1966

Brauer, Joseph B., "Poor QC Yields Bad IC's," The Electronic Engineer, August 1966

Buckley, J. J., "The Nonoperating Failure Rate - A Valuable Reliability Tool," Proceeding Eleventh National Symposium on Reliability and Quality Control, Miami Beach, Florida, pp 434-438, January 1965

Burns, J. G., "Resistors Fixed Film Type General Purpose," AD 296-292, September 1962

Caggegi, F., "Determination of Shelf Life of O-Ring and Slot Filler for AIM-9B MK 303 Fuze Assembly," AD 464-765, June 1965

Carroll, J. F., "Study of Failure Mechanisms in High-Power Radio-Frequency- Generator Devices," RADC-TDR-64-290, AD 608-362, September 1964

Charko, J. P., King, T. E., Lackner, J. L., Dudois, A. R., Moroz, W. J., Wright, N. C., Wilson, L. G., Haines, R. L., Coleman, J. R., and Casey, E. J., "Studies on Zinc-Silver Oxide Batteries," AD 340-214, May 1963

Clark, L. D., Burrus, J. C., and Clark, R. D., "Evaluation of Selected Methods For Detecting Contaminants Within Semiconductors," Institute of Environmental Sciences' 1965 Annual Technical Meeting Proceedings, pp 65-71, 1965

Conrad, G. T. and Shook, D. C., "A Transistor Aging-Behavior Experiment for a Low-Power Switching-Type Transistor," Report No. 2, NBS Project 1401-20-14491, NBS Report 7324, 16 August 1961

Conrad, G. T. and Shook, D. C., "A Transistor Aging-Behavior Experiment for a Low-Power Switching-Type Transistor," Report No. 3, NBS Project 1401-12-14491, NBS Report 7488, 20 April 1962

Conrad, G. T. and Shook, D. C., "A Transistor Aging-Behavior Experiment for a Low-Power Switching-Type Transistor," NBS Project 1401-12-14491, AD 441-334, September 1963

Cullari, C. C., "Standardization Study on Reliability of Quartz Crystal Units Final Report," Associated Testing Labs, Inc., Wayne, New Jersey, and Burling, Massachusetts, AD 450-471, 26 June 1962

Dahlem, R. K., "Thirteen Key Questions on Semiconductor X-Ray Evaluation," Evaluation Engineering, Vol 3, March - April 1964

Dodson, G. A. and Howard, B. T., "High Stress Aging to Failure of Semiconductor Devices," Proceedings Seventh National Symposium Reliability and Quality Control, p 262, January 1961

Doyle, P. J., "Effects of Storage and Testing on Terrier Success Rates," U. S. Naval Ordnance Laboratory, Technical Memo No. 62-117, 28 May 1956, Confidential

Dummer, G. W. A., "Electronic Component Parts Failure Rates and Failure Mechanism Research in the United Kingdom," IEEE Transactions and Component Parts, Vol CP-11, June 1964

Easterday, J. L., "Integrated Circuit Reliability," Battelle Memorial Institute, Columbus, Ohio

Embrace, M. L., "Semiconductor Device Rating - Their Determination and Use in Reliable System Design," Semiconductor Reliability, Vol 2, pp 190-210, (1962)

Feduccia, A. J., "Reliability Screening Using Infrared Radiation," Proceedings for the Society for Nondestructive Testing, Inc., October 1964

Ferguson, R. L., "No-Test No-Maintenance Economics," IEEE Transactions on Aerospace, Vol AS-1, Proceedings of the International Conference on Aerospace Support, pp 889-894, August 1963

Fewer, D. R. and Gill, W. L., "Investigation of Reliability Testing and Prediction Techniques for Integrated Circuits," AD 489-969, August 1966

Ficchi, R. F. and Raphelson, M., "Storage of Electronic Components and Equipment," Communications System Division, RCA, Camden, New Jersey, May 1964

Francone, F. J., "Effects on Storage of Electronic Component Parts," JPL Section Report 16-34, R79893, Pasadena 3, California, 11 November 1954

Gauger, G. W., Easterday, J. L., Mitchell, R. I., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 424-657, 5 July 1963

Gauger, G. W., Easterday, J. L., Mitchell, R. I., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 424-692, 30 September 1963

Gauger, G. W., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 431-283, 9 December 1963

Gauger, G. W., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 431-501, 3 February 1964

Gauger, G. W., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 439-078, 31 March 1964

Gauger, G. W., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 441-959, 31 May 1964

Gauger, G. W., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, AD 444-814, 31 July 1964

Gauger, G. W., Knuth, D. T., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, 30 September 1964

Carlson, H. G., Gill, W. L., and Hall, J. E., "Investigation of Reliability Testing and Prediction Techniques for Integrated Circuits," Technical Report No. RADC-TR-65-463

Gauger, G. W., Knuth, D. T., Roppel, R. M., Spradlin, B. C., Easterday, J. L., and Davidson, R. S., "Progress Report on Microbial Deterioration of Electronic Components," Battelle Memorial Institute, Columbus, Ohio, 18 January 1965

Go, H. T., "Integrated Circuits: How and Why They Fail," Circuit Design Engineer, pp 93-95, January 1966

Go, H. T., "Studying and Controlling IC Reliability," Electronic Industries, pp 40-44, February 1966

Gomberg, L. and Thierfelder, H., "Assuring Reliability in Aerospace Batteries," Proceedings Eleventh National Symposium on Reliability and Quality Control, pp 459-469, January 1965

Grover, Robert, "Effects of Hole Storage and Temperature," DOFL-TR-570

Hadley, W. R. and Patterson, R. T., "System Survival in the Nonoperating State," Annals of Reliability and Maintainability, July 1965

Hart, R., "Investigation of Q Degradation of RF Coils During 125°C Storage," AD 459-977, IDEP No. 181.00.14.47-54-01, August 1964

Herrold, G. R., "Failure Rate by Mode of Failure Data," Proceedings Eleventh National Symposium on Reliability and Quality Control, pp 480-486, January 1965

Hewitt, C. M., Jr., "Analysis of Hawk Round NR48," Missile 01165E, WSMR-TM-712, June 1960, Confidential

Holcomb, R. A., "Evaluation and Control of Residual Moisture in Hermetic Relays," Proceedings Twelfth Annual National Relay Conference Sponsored by National Association of Relay Mfg. and School of Electrical Engineering, OSU, Stillwater, Oklahoma, April 1964

Holden, P., "Integrated Circuit Reliability Assessment," Texas Instruments, 1 January 1966

Hsiao, C. C., "Fracture," Physics Today, pp 49-53, March 1966

Johnson, E. S., "Reliability Assessment of U. S. Air Force Stockpile of Bullpup AGM-12B G&C Sections Phase II," QE/SB 65-39, September 1965, Confidential

Kapfer, V. C., "Failure Mechanisms at Metal-Dielectric Interfaces," AD 603-279, RADC-TDR-64-138, July 1964

King, J. R., "Data Analysis in Physics of Failure Studies," Transactions Nineteenth Annual Technical Conference American Society for Quality Control, Los Angeles, California, pp 242-248, May 1965

Lee, R. W. H., "Effects of Storage on Electronic Equipment and Components, A Preliminary Literature Survey," AD 601-311, 6 December 1962

Luciani, C., "Assessment of Magnesium Case "D" Type Dry Cells," Canada/DQMG, Report 106 (CMH/Report) B-57597

Margoshes, H. M. and Thomas, J., "Reliability Report on Philco High-Speed PNP Transistors Sylvania Specification," AD 292-593, March 1962

Meyland, R. F., "Age and Deterioration Test Program," RD 22-1, Rev 6, Part 1, Martin Marietta Corporation, Orlando, Florida, December 1965, Confidential

Meyland, R. F., "Age and Deterioration Test Program," RD 22-1, Rev 7, Part 1, Martin Marietta Corporation, Orlando, Florida, April 1966, Confidential

Misra, R. P. and Dworkin, E. J., "A New Method for Predicting Reliability," Electronic Industries, June 1966

Mills, G. W., "A Comparison of Permanent Electrical Connections," Bell Systems Technical Journal, Vol XLIII, No. 3, May 1964

Morris, R. L. and Wollin, Davis, "Evaluation of the Effect of X-Ray Detectable Defects on the Performance of Semiconductors," Lockheed Missiles and Space Company, Sunnyvale, California

Nerber, P. O., "Power-Off Time Impact on Reliability Estimates," 1965 IEEE International Convention Record Part 10, New York, New York, pp 1-8, March 1965

Pace, F. D., "Reliability of Minuteman Operational Ground Equipment," Proceedings Eleventh National Symposium on Reliability and Quality Control, pp 324-330, January 1965

Packard, C. C., "Reducing Reliability Risks Through Failure Analysis, Screening and Process Improvement," Semi-Conductor Reliability, Vol 2, pp 91-99, (1962)

Pittman, P., "Integrated-Circuit Reliability," Electro Technology, January 1966

Porter, D. C., "Failure Analysis of Electronic Parts," IEEE Transactions on Reliability, Vol R-14 No. 1, pp 56-65, March 1965

Porter, D. C., "Studying Gross Abuse of Semiconductor Devices," Space Aeronautics, Vol 42, pp 78-79, August 1964

Queisser, H. J., "Stacking Faults and Failure of Silicon Devices," Physics of Failure in Electronics, Vol 2, AD 434-329, pp 476-482, (1964)

Randle, W. R., "Infrared Testing of Electronic Components," OR 6610, Martin Marietta Corporation, Orlando, Florida, June 1965

Raymond, G. A., "Second Thoughts on Reliability," IEEE Transactions on Reliability, Vol R-14, No. 1, pp 66-75, March 1965

Redler, W. M., "Parts Reliability Problems in Aerospace Systems," 1966 Annual Symposium on Reliability, pp 212-220

Reinhartz, K. K., Russell, V. A., Stockman, D. L., van der Grinten, W. J., and Willis, W. L., "Aging Characteristics of Field Effect Thin Film Active Devices," Proceedings 1964 Electronic Components Conference Sponsored by IEE and EIA with Participation of ASQC, Washington, D. C., May 1964

Reinhartz, K. K., Russell, V. A., Stockman, D. L., van der Grinten, W. J., and Willis, W. L., "Failure Mechanisms at Surfaces and Interfaces," RADC-TDR-64-454, AD 613-036, February 1965

Schiavone, D. C., "STORE-Storage Technology for Operational Readiness," American Ordnance Association, China Lake, California, April 1965

Schnable, G. L., Schlegel, E. S., and Keen, R. S., "Failure Mechanisms in Reverse-Biased Oxide-Passivated Silicon Diodes," Physics of Failure in Electronics Third Annual Symposium, 1964

Schroen, W. and Hooper, W. W., "Failure Mechanisms in Silicon Semiconductors," Shockley Research Laboratory, Palo Alto, California, AD 615-312, RADC-TR-64-524, March 1965

Schramp, Joseph M., "Metallization Failures in Semiconductor Devices," Rome Air Development Center

Severson, Donald M., "Service Life Test on Hawk Missiles," White Sands Missile Range TM-1126 (c), August 1963

Smith, K. W. and Rubeck, B., "Sergeant Shelf and Storage Life Rounds 1 and 2," AD 3[illegible], March 1965

Struss, C. J., "How to Evaluate Resistor Design Tolerances," Evaluation Engineering, Vol 2, January - February 1964

Stiles, A. M., Jr., "Phase I Research and Investigation Survey for the Long Life Verification of Hardware," Final Report ER-14103, Martin Baltimore, December 1965

Thomas, R. E. and Gorton, H. C., "Research Toward a Physics of Aging of Electronic Component Parts," Physics of Failure in Electronics, Vol 2, AD 434-329, pp 25-185, (1964)

Thompson, E. E., "Handling, Storage and Transportation of Guided Missiles and Guided Missile Components," (Bibliography), AD 344-930, November 1963, Secret

Tier, R. J., "Effect of Environmental Condition on Diodes," AD 425-261, April 1963

Walsh, T. M., "Accelerated Test Program," Final Report Contract No. AF30(602)3415, General Electric, 10 July 1965

Weiss, G. H., "Optimal Periodic Inspection Programs For Randomly Failing Equipment," Journal of Research of the National Bureau of Standards B. Mathematics and Mathematical Physics, Vol 67B, pp 223-228, October - December 1963

West, P., "Why Plastics Don't Live up to Design Data," Product Engineering, pp 80-82, 25 April 1966

Willstadter, R., "Dormant Missile System Checkout Effectiveness," Proceeding Tenth National Symposium on Reliability and Quality Control, pp 612-523, January 1964

Wright, J. and Alexander, M. B., "Industrial Preparedness Study on Devices 13, 14, 15 Extended Life Test 8000 Hour Data Report," AD 294-847, November 1962

Yereance, R. A., "Unified Index - Issue 4," Electronic Component Reliability Center of BMI, Columbus, Ohio, March 1965

"Accelerated Testing of High Reliability Parts," AD 617-141, May 1965

"Accelerated Testing of High Reliability Parts," AD 610-943, January 1965

"Consolidated Aging Study Program for the LGM-30 Weapon System, Vol II, Re-Entry Vehicle," TRW Space Technology Laboratories, Redondo Beach, California, 30 June 1965, Secret

"Consolidated Aging Study Program for the LGM-30 Weapon System Final Report Vol III, Penetration Aids," TRW Space Technology Laboratories, Redondo Beach, California, 30 June 1965, Secret

"Consolidated Aging Study Program for the LGM-30 Weapon System, Vol IV, Propulsion," TRW Space Technology Laboratories, Redondo Beach, California, 30 June 1965, Confidential

"Consolidated Aging Study Program for the LGM-30 Weapon System, Vol V, Guidance and Control, Final Report," TRW Space Technology Laboratories, Redondo Beach, California, 30 June 1965, Secret

"Consolidated Aging Study Program for the LGM-30 Weapon System, Vol VI, Airframe and Ordnance, Final Report," TRW Technology Laboratories, Redondo Beach, California, 30 June 1965, Confidential

"Detailed Study of Deleterious Effects on Silicon Transistors," RADC-TDR-64-352, AD-609-065

"Deterioration of Electrical Insulation," Engineering, Vol 192, PDL-42232, pp 662-663, November 1961

"Determination of Reliability Degradation of SCN Component Parts During Storage," WE133A MTOR-C-049, RCA Service Company, 3 February 1961

"Dormant Missile Inertial Guidance and Control System Component Survey, Vol 1," AB 1210-0006-2, AD 347-815, June 1963, Secret

"Dormant Missile Inertial Guidance and Control System Component Survey, Vol 2," AFBSD-TN-63, AD 347-820, Sperry Rand Corp., July 1963

"Dormant Missile Inertial Guidance and Control System, Phase I Study Programs," Supl Task 2, AFBSD-TN-63, Sperry Gyroscope Company, June 1963

"Dormant Missile Inertial Guidance and Control System, Phase I Study Programs," Supl Task 3, Sperry Gyroscope Company, Report No. AB 1210-0010-3, July 1963

"Dormant Missile Inertial Guidance and Control System, Phase I Design Study Program," AFBSD-TR-63, AD 347-822, August 1963, Secret

"Dormant Missile Inertial Guidance and Control System Trade-Off Studies, Vol 3," AB 1210-006, AD 347-816, Sperry Gyroscope Company, June 1963, Secret

"Environmental Effects on Materials and Equipment," Abstracts Vol 4, No. 1, Sec A, AD 433-649, Prevention of Deterioration Center, January 1964

"Evaluation of Effects of Shelf Life on Capacitors (General Purpose)," Lab Project 4960-U-2, Part 2 Prog Report 15, Problem 110-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 26 January 1960

"Evaluation of Effects of Shelf Life on Capacitors (Mica and Ceramics)," Lab Project 4960-U-2, Part 2 Prog Report 16, Problem 1101-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 7 March 1961

"Evaluation of Effects of Shelf Life on Capacitors," Lab Project 4960-U-2, Part 2 Prog Report 17, Problem 110-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 11 August 1961

"Evaluation of Effects of Shelf Life on Paper Dielectric Capacitors," Lab Project 4960-U-2, Part 2 Prog Report 22, Problem 1101-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 10 April 1963

"Evaluation of Effects of Shelf Life on Mylar Capacitors," Lab Project 4960-U-2, Part 2 Prog Report 23, Problem 1101-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 16 May 1963

"Evaluation of Effects of Shelf Life on Fixed Film Resistors (MIL-R-10509A)," Lab Project 4960-U-2, Part 4, Final Report, Problem 1101-U-2, Material Laboratory, New York Naval Shipyard, Brooklyn 1, New York, 10 October 1963

"Failure Mechanisms in Microelectronics," RADC-TDR-64-252, AD 609-426, August 1964

"Long Term Storage Effects," Defense Documentation Center, ARB-No. 040181, 24 September 1965, Secret

"Long Term Storage Study Final Report," RCA Service Company, 6 November 1963

"Micromodule Life Test," 1st Quarterly Progress Report, Contract No. DA36-039-AMC-0146Z(E), RCA, March 1965

$\mu$ - notes, Volume 12, NAD, Crane, Indiana, AD618-094

$\mu$ - notes, Volume 13, NAD, Crane, Indiana, AD471-696

$\mu$ - notes, Volume 14, NAD, Crane, Indiana, AD472-435

$\mu$ - notes, Volume 16, NAD, Crane, Indiana, AD635-626

"Physics of Failure in Electronics," RADC, Voi 3, Air Force Systems Command, AD 617-715, April 1965

"Physics of Failure in Electronics, Fourth Annual Symposium Papers," Autonetics Report No. X5-1977/3111, Anaheim, California, November 1965

"Reliability Aspects of Dormancy and Storage," U. S. Army Missile Command, Redstone Arsenal, 8 December 1965, Confidential

"Reliability Report, Semiconductor Networks," Texas Instruments, 1963

"Reliability Data," Westinghouse Electric Corporation, August 1966

"Reliability Assessment of Stockpiled GAM-83A Nose Sections," Martin OR 3482, September 1963

"Resistor, Fixed, Non-Wirewound," AD 415-513, October 1962

"Semiconductor, Device, General Purpose, Diode High Reliability SCD," AD 401-958, September 1962

"Semiconductor Reliability," Final Report on Contract NObsr 87664, AD No. 416492, ARINC Research Corporation, 31 July 1963

"Shelf and Service Life Determination of Nike-Ajax Missiles," Electro-Mechanical Laboratories Division, White Sands Proving Ground, New Mexico, February 1958

"Status Report of Integrated Circuits Reliability," Microelectronics and Reliability Vol 4, pp 315-330, December 1965

"Techniques for the Control of Integrated Circuit Quality and Reliability," IR-8-232, Air Force Materials Laboratory, Wright Patterson Air Force Base, July 1966

"Tropical Service Life on Electronic Parts and Materials," Fourth Quarterly Progress Report, Report No. 5, U. S. Army Electronics Laboratories, Fort Monmouth, New Jersey, 31 July 1964

"Tropical Service Life of Electronic Parts and Materials," Fifth Quarterly Report, Report No 6, U. S. Army Electronic Laboratories, Fort Monmouth, New Jersey, 31 October 1964

"Two Self-Healing Circuits: One Grows Whiskers, Second Solders Breaks," Machine Design, Vol 36, p 12, 2 January 1964